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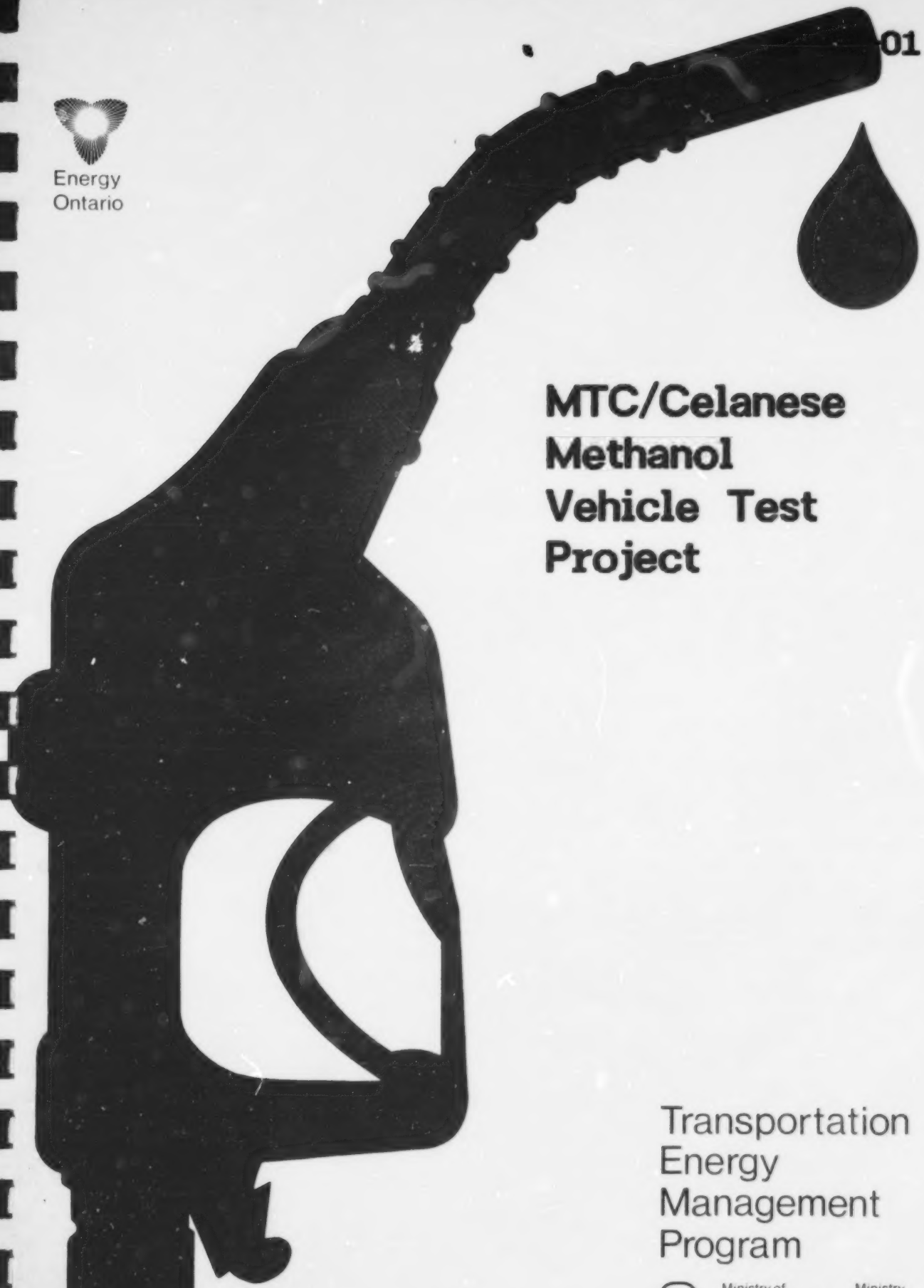

MTC/Celanese Methanol Vehicle Test Project

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MTC/Celanese Methanol Vehicle Test Project

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Another Ford Escort was also operated in a long-distance accumulation mode to examine engine durability on M90. The engine was pre-measured after being run in and then stripped for measurement after about 30 000 km. Regular oil sampling and analysis was maintained during the period to supplement the wear appraisal. The results showed that with a few exceptions, component dimensions were within the manufacturers' acceptable tolerances after the distance accumulation.

Key Words: methanol vehicle, methanol fuel, oil testing, cold starting, engine wear

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ABSTRACT

Methanol fuel formulations have been devised containing oxygenated, methanol-derived volatility primers instead of the customary hydrocarbon components. These were tested on two available methanol vehicles, a Ford Escort and a VW Golf, to determine if adequate low temperature startability could be obtained. The first round of fuels tested, containing dimethyl ether and dimethoxymethane, did not extend startability beyond that achieved with M90 (methanol, 90%; gasoline, 10%). However, the volatilities employed were below the maximum permissible, and tests with greater concentrations are to be carried out.

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1/ INTRODUCTION

Methanol is the simplest of all combustible organic compounds that is liquid at normal temperatures, and it is the easiest to make in industrial quantities. It can be made, in principle, from any carbon-containing material and thus, from many resources available in Canada, including natural gas, coal, and biomass. Because of its cheapness, natural gas is used for production in Canada, and of about 1.9 million tonnes of methanol produced annually, all but 0.25 million tonnes is surplus to domestic requirements and is exported (1984). Consequently, methanol is a likely first choice as a substitute for conventional hydrocarbon fuels when the cost and supply of the latter make it economic to do so.

Because methanol has quite different physical and chemical properties than hydrocarbons, it cannot be used straight in unmodified engines. Optimum use of the fuel generally requires that it be modified with additives and used in an engine that has been suitably redesigned. For spark-ignition engines, the principal alteration to the fuel is to raise its volatility with additives to facilitate starting at low temperatures.

Hydrocarbons have been used for this purpose in a number of trials, including some conducted or sponsored by the Ministry of Transportation and Communications (MTC), e.g., using iso-pentane [1] or gasoline (with and without dimethyl ether) [2,3]. Hydrocarbons such as these seem to have reasonable cold-starting performance but may not be so adequate in other respects. For one thing, they form very non-ideal mixtures with methanol because of their chemical dissimilarity, and this may result in poor retention of the more volatile component in storage (poor weatherability). The tolerance of hydrocarbon/methanol mixtures to water is also limited. In the long-term as well, it may be desirable to devise a fuel based entirely on synthetic products. Also, following present-day practice with gasoline, better drivability performance over wide seasonal variations may be obtained when the fuel contains a number of different components of graded volatility to provide a sloping boiling characteristic.

In the present project, methanol-based fuels have been devised using certain synthetic oxygenated components as volatility primers. Three compounds have been considered so far -- dimethoxymethane (methylal, DMM), dimethyl ether (DME), and methyl formate; all can be made from methanol itself by low energy processes not involving carbon-carbon synthesis. These components could, therefore, be made cheaply in bulk-fuel quantities as part of an entirely synthetic fuel economy.

The present project is jointly sponsored by MTC and Celanese Canada. Celanese Canada has devised fuel mixtures and determined some basic physical properties. MTC has carried out cold startability and other tests on these fuels, using two available methanol-designed engines.

2/ FUEL PROPERTIES

The basic physical and chemical properties of methanol and the three components derived from it are shown in Table 1. The two important characteristics that could impart startability to the fuel mixture are high vapour pressure and low flammability limit. DME is best from both points of view but, being a gas at ordinary temperatures, is more troublesome to handle during the blending stage and is likely to be rapidly lost during storage. The other two components are also more volatile than methanol, and DMM, particularly, has a much lower flammability limit. The chemical stability of all components is good; however, there is a possibility that methyl formate might be easily hydrolysed during storage or under engine conditions and, thereby, liberate corrosive formic acid.

In the first selection of fuels by Celanese, methyl formate was eliminated as a potential component, and the other two components were employed to make three fuel mixtures, as described in Table 2. Also included in this table is the baseline fuel mixture against which they are being compared, M90 (i.e., 90% methanol and 10% winter grade gasoline).

3/ TEST VEHICLES

Two types of factory-built vehicles have recently become available and are described in Sections 3.1 and 3.2.

3.1/ Ford Methanol Escort

In response to an order originating in California, approximately 500 vehicles were designed and built by the Ford Motor Company to run on straight methanol. MTC acquired two of these, and some others are being used in projects supported by MTC. Because of their intended use in California they have not been designed particularly to accommodate the more rigorous climate typical of Ontario, even though the manufacturer has made some adjustments in calibration. The engine is an overhead cam (OHC), four-cylinder, cross-flow head design with a capacity of 1.6 L and a compression ratio (CR) of 11.8:1. The principal changes over the stock engine are the increase in CR, the use of methanol-tolerant materials in the fuel system, a provision for increasing upper cylinder lubrication, and a larger early fuel evaporator (EFE) in the intake manifold to supply extra heat during starting. A detailed list of the changes is given in Table 3, and a diagrammatic representation of the intake system is shown in Figure 1.

3.2/ VW Methanol Golf

This vehicle, imported from Germany, is the result of a longer and more mature development program. However, it has not been developed for North American emission standards. The engine is an OHC, 1.6 L four-cylinder, with a U-flow cylinder head design and a CR of 12.5:1. Besides the use of methanol-tolerant components in the fuel supply system, the principal adaptation is an extensively redesigned inlet manifold (Figure 2), with a heat exchanger supplied with engine coolant and a large electrically heated plenum for aid in cold starting and drivability.

4/ TEST PROGRAM

The principal problem areas associated with methanol use in vehicles are cold-weather operation and engine durability. The VW Golf and one of the Escorts were assigned to a test program to evaluate the novel fuel mixtures for startability, while the other Escort was put in a distance accumulation mode.

4.1/ Fuel Dispensing Facilities

The baseline M90 was delivered by Celanese to a 4546 L (1000 gal) underground storage tank at the MTC Downsview site. The pump was an Astro universal suction pump with some modifications. To resist the possibility of corrosion, all the aluminium components were supplied nickel-plated. Also, the seals were made of a low-swelling viton compound, and the fuel hose was lined with Teflon. The special test fuels were supplied by Celanese in 204.6 L (45 gal) drums.

4.2/ Equipment

The vehicles were stored in a refrigerated chamber (Figure 3) for cold-start testing. This was a 2.6 m (102 in) semitrailer supplied by Pullman Trailmobile Canada Ltd., Brantford, Ontario. The wheels of the trailer were removed, and it was permanently located in the District 42 area at MTC, Downsview, Ontario. The compressor used to refrigerate the trailer is supplied by Thermoking Corporation of Toronto, Transport Refrigeration Ltd., Mississauga, Ontario.

The baseline fuel (M90) was kept in the vehicle fuel tank and used for calibrating the vehicle between tests. The fuel under test was placed in an auxiliary tank, a stainless steel pressurized fuel cannister supplied by the Cornelius Company, Anoka, Minnesota (Figure 4).

4.3/ Vehicle Instrumentation

The two vehicles were instrumented with temperature sensors at various positions of the engine intake system to monitor the vehicles' cold-

start and warm-up characteristics. For the Escort, the temperature sensors were installed in the following locations:

- inlet manifolds No. 1, 2, and 4
- carburetor heater spacer
- intake manifold spacer
- air intake

For the VW Golf, the sensors were installed as follows:

- intake manifolds No. 1 and 2
- heater plenum
- manifold spacer
- air intake

In addition, a revolutions per minute (rpm) sensor was installed in each vehicle to monitor the engine speed and to identify the total cranking time to start the vehicles. The exact locations of these sensors are also shown in Figures 1 and 2.

During the cold-start test, the signals from the sensors were fed into the amplifier and recorded on a chart recorder. A diagrammatic layout of the instrumentation is shown in Figure 5.

All of the chart recording temperatures have an 80°C range on the chart strip, i.e., channels 1 to 5. Channel 6 records an engine speed reading to a maximum of 800 rpm, and channel 7 records it to a maximum of 4000 rpm.

Since the signal outputs from the two test vehicles were different, the chart recorder and signal amplifier were set according to each vehicle. Table 4 specifies all the settings.

Before the vehicles were subjected to the cold-starting tests, the heating characteristics of the heater were first studied, as described in Appendix A.

4.4/ Cold-Start Test Procedure

Each of the test vehicles was filled with one of the four test fuels, and the vehicle was cooled overnight in the temperature-controlled trailer. The initial test temperature was set at 0°C, with a succession of lower temperatures until starting was impossible, e.g., -10, -15, -20°C, etc. Before each test, the temperature of the engine coolant was checked to obtain the actual initial starting temperature. The cranking speed was maintained relatively constant via the use of a battery charger and electric blanket. Since the Golf is equipped with a manual choke and the heating characteristics of the heater are different from the Ford Escort, the starting procedures for the two vehicles are different (Appendix B). The major difference in the two procedures is that the choke control in the Golf is set to its maximum position and a longer preheating time (approximate 25 s) is used before the cranking begins.

After starting the vehicle, it was allowed to warm up for 15 min to record the warm-up characteristics of the engine. If the vehicle did not start, it was removed to a warmer area, started, and run for at least 15 min before the preparation of the next test. This procedure is important because prolonged cranking results in oil dilution and would cause severe engine wear. Thus, the engines must be warmed up completely to vaporize the unburned fuel before the next test.

4.5/ Engine Components and Wear

One of the Ford Escorts was run with M90 and driven by MTC technical staff for distance accumulation. The long-term engine component wear was closely examined by detailed measurements of the engine parts and used-oil analysis.

The first involved the appropriate measurements of key engine parts, such as cylinder bore diameter, piston diameter, camshaft lobe or lift, valve stem and guide diameter, or piston ring gaps, after the vehicle had been run in.

The vehicle was then put on extended distance accumulation, with oil sampling for wear metal analysis every 2000 km. Bulk-oil properties were

also checked at oil-change intervals. At 33 670 km, the vehicle was stripped again for a direct check of component wear.

5/ RESULTS AND DISCUSSION

5.1/ Engine Cranking Speed

The prerequisite of a good cold-start test is to maintain a constant cranking speed. In the cold-start tests, the engine cranking speed was maintained constant, even at low ambient temperatures and prolonged cranking periods, by the use of an external battery. Even at -16°C, there was no variation of cranking speed, with cranking time up to 233 s. In addition, the use of the battery not only maintained the cranking speed but also increased it at low ambient temperatures. Table 5 shows the variation of the cranking speed with or without the external battery at different ambient temperatures. Only the Ford Escort showed an increase in engine rpm, but this increase of cranking speed was not very significant at intermediate temperatures (-4° to 3°C), that is, the speed only increased from 310 to 340 rpm. However, at low temperatures (-12 to -20°C), the cranking speed was greatly increased from 100 to about the normal cranking speed of 300 rpm. This illustrated that without the use of the external battery, the cranking speed would be too low to turn over the engine adequately. Hence, the use of the auxiliary battery was essential to keep a constant cranking speed at all test temperatures.

5.2/ Heater Characteristics

The heating characteristics and heater location in the engine intake system affects the amount of vaporized methanol fuel and, consequently, the startability of the vehicle. To maximize the heating capacity of the heater, an optimum preheating period must be established before the first engine cranking. The optimum preheating period is mainly determined by the rate of temperature rise and the maximum temperature attained by the heater. Table 6 shows the temperature rise of the Golf and Escort heaters during the preheating period. The rate of heating of the Ford Escort heater was greater than the Golf; however, the Golf was heated up for a longer period of time and would, therefore, reach a higher final temperature, usually 10°C higher than for the Escort. At low ambient temperature, -12 to -20°C, the maximum temperature reached by the Escort heater was 21.52°C, and the rate of temperature rise was 2.897°C/s. For the Golf, the maximum heater temperature was 29.14°C, and the rate of

temperature rise was 0.887°C/s. This indicated that the Golf's heater was warming up approximately 3.5 times slower than the Escort heater. Hence, the initial preheating period of the Golf was allocated a longer time of 25 s, whereas the Escort was allocated a shorter period of 10 s before the first cranking in the cold-start tests.

The location of the heater in the intake system also affects the degree of fuel heating during the preheating period Figures 6 and 7 show the temperature profile during cranking at various sites in the intake system for the two vehicles. For the Ford Escort, the temperature of the carburetor spacer was the highest among all the locations in the intake system. After the 10 s initial preheating period, the temperature of the spacer dropped each time the fuel was added, giving a total of six ridges in the temperature profile. As soon as the cranking started, the battery power was cut off from the heater so that no heating was available and the spacer cooled right down. Then, during the interval between cranking, the spacer heated up once more. In subsequent cranking sequences, the cycle was repeated, with the spacer temperature generally getting lower. At ambient temperatures from -4 to 3°C, the average temperature reached by the spacer on subsequent starting attempts was 46.0°C, while at -12 to -19°C, the average spacer temperature reached was only 12.7°C (Table 7). For the VW Golf, the variation of the temperature profile of the heater spacer was not very large. As, compared to the Escort, the size of the heater of the VW Golf is larger and is located at the bottom of the intake manifold, there was a larger residual mass to be heated, and consequently, the temperature variation was smaller.

The location of the heater inside the intake system also affects the temperature of the air-fuel mixture in the intake runners. For the Escort, the two outer runners heat up more quickly than the inside one, No. 2 showing considerable non-uniformity in the flow pattern. With the Golf, the inside and outside runners show similar temperatures.

5.3/ Cold-Start Tests

Cold-starting tests have been completed for both test vehicles on all four test fuels. The results are summarized in Table 8. The raw test

data are listed in Tables 12 to 18 and are graphically represented in Figures 8 and 9. For the ease of comparison between the cold-starting performance of the test fuels, the starting temperatures of the two test vehicles at the 30 and 45 s cranking period were recorded and listed in Table 8. The cold-starting performance of the base fuel, d)(M90), was the best among all the test fuels because both test vehicles showed the lowest starting temperatures at 30 and 45 s cranking periods. At 30 s cranking, the Escort could start at -10.5°C, and the VW Golf, at -15°C. At 45 s cranking, the Escort could start at -14°C, and the Golf, as low as -18°C.

Fuel c) (3.4% DME and 10% DMM in methanol) was the second best in cold-starting performance. However, the starting temperature difference was not large compared to M90. In general, the cold-starting temperature of this fuel was only 1.0°C higher than the values of M90 at 30 s cranking time. At 45 s cranking, both vehicles showed the same starting temperature of -16.5°C.

The remaining two fuels were significantly poor in cold-starting performance. The one with the higher DME concentration (and vapour pressure), b), is the least effective of all the fuels, supporting evidence elsewhere [1,2] that too high a concentration of high volatility components is counterproductive because of over-richening. The advantage of c) over a) and b) may also be due to the low lean limit for DMM.

In addition, there was a significant difference between the cold-starting performance of the two test vehicles. Overall, the starting temperature of the Golf was lower than the Escort for all test blends. For M90, the Golf could start at -15°C with 30 s cranking, but the Escort could only start at -10.5°C. At 45 s cranking, the Golf could start as low as -18°C, whereas the Escort showed no sign of starting at this temperature. The better cold-starting performance of the Golf was mainly because of the design and location of its heating element, which affected the temperature profile of the intake manifold runners, particularly during the preheating and the first cranking period.

5.4/ Temperature Profiles of Intake Manifolds

The temperature profiles of the intake manifolds give an indication of the amount of heat available to vaporize the test fuel and, consequently, affect the cold-starting performance of the vehicles. At the first cranking, the Golf showed an increase in temperature in the intake manifolds, whereas the Escort did not. The temperature rise of the Golf was about 4°C throughout the cold-starting temperature ranges, with the temperature rise in the second intake runner being the highest. Table 9 shows the values of the temperature increase in the intake manifold of the Golf. The higher temperature profile of the intake runners indicates that a warmer air-fuel mixture is drawn into the engine during cranking for the VW Golf than for the Escort.

Tables 10 and 11 show the temperature of the intake manifolds of the two test vehicles just before the first firing. At about the same cold-starting temperature, the temperature of the intake manifolds of the Golf ranges between 5 to 17°C higher than the Escort. This further implies that a larger amount of ignitable mixture was available in the combustion chambers of the Golf.

The higher manifold temperature profile of the Golf is due to the design and location of its heater, which is situated at the bottom of the manifold assembly. The fuel was heated directly on top of the heater and was only drawn into the combustion cylinders during cranking. Consequently, the fuel vapour has a shorter passage to travel before entering into the engine, and the degree of fuel recondensing is reduced. For the Ford Escort, the degree of fuel recondensation is higher because the fuel was only heated during its passage through the carburetor spacer. The vaporized fuel has to travel a longer distance before reaching the cylinders. This fuel mixture would cool or recondense in the cold intake manifold assembly before entering into the combustion chambers. Hence, the temperature profile of the intake runners of the Escort was often lower than the Golf, and consequently, its cold startability is inferior.

5.5/ Engine Warm-up Conditions

The manifold temperatures of the two vehicles during the 15 min warm-up period after starting are shown in Figures 10 to 12 for a few fuels. For both vehicles, the inlet air rose quite steadily during the warm-up period. During the first 5 to 7 min of operation, the rate of heating of the inlet air did not change with changing engine speeds. After approximately 7 min of operation, however, with engine rpm speed reduced by kicking down the choke, the inlet air experienced a drastic drop in temperature, but soon regained its original rate of heating.

Of the Escort intake manifolds, No. 2 and 3 are always the hottest, and No. 1 is always the coolest. This is due to the engine design and placement of the exhaust gas recirculation (EGR) valve. Between intake manifold cylinders No. 2 and 3 there is a section where the coolant is routed. This keeps these two manifold sections warmer than the rest during hot-engine driving conditions. Manifold No. 4 contains the EGR valve; therefore, it will logically be warmer than manifold No. 1, although the two warm-up curves are very similar. After approximately 12 min of operation, the inlet air on the Escort reached approximately 25°C for higher ambient temperatures (+1 to -5°C range), but only 15°C in the -13°C region.

On the VW Golf, intake No. 1 is almost always the warmest of the two being monitored. The curves of manifolds No. 1 and 2 also follow each other closely, like manifolds No. 1 and 4 on the Escort. After the engine was warmed up for 5 min, the manual choke was depressed, causing a sudden drop in temperature profile of all intake manifolds. The engine was allowed to warm up and the temperatures in the manifolds tended to stabilize somewhat after approximately 12 min of operation.

5.6/ Methanol Vehicle Durability

During the initial runs, the drivers repeatedly reported that the engine knocked at approximately 90 km/h. After the vehicle had travelled for 6000 km, the engine finally failed because of overheating, apparently from preignition. The vehicle was towed back to the MTC test centre and the engine was dismantled and examined. The complete engine tear down results are shown in Appendix C.

The engine examination indicated that there were two severely burned spark plug electrodes at cylinders No. 1 and 3, caused by the extreme heat fusing these electrodes (Figure 13). The intake valves were also damaged and the surfaces were dished, especially at cylinders No. 1 and 3 (Figure 14). The valve seals were worn extensively and the valve stem at No. 3 cylinder was extended. The compression rings were also damaged extensively, with the ring gap measurements out of specification.

A large amount of carbon deposit was found in intakes No. 2 and 3 valve stems. A close examination of the intake manifolds showed that intake runners No. 2 and 3 were unusually clean, without any deposit, whereas runners No. 1 and 4 showed typical brownish deposits. This indicated the effect of uneven fuel distribution caused by intake manifold design, which resulted in a larger amount of fuel entering into cylinders No. 2 and 3. Consequently, the normal brownish deposits at the corresponding intake runners were washed away by the excess fuel. In addition, the excess fuel formed an overly rich combustion mixture and burned in the cylinders, with the lubricant forming the black deposits (Figure 15), and flushed back to the intake stems in runners No. 2 and 3.

After the engine inspection, the extensively damaged piston rings, intake and exhaust valves, and seals were all replaced by new parts supplied by Ford. The initial spark plugs, AWSF12C, were also replaced by AGSF12C, which was for the same heat range but had a different material composition of the side electrode than the former plug.

The engine was reassembled and the vehicle was used again for distance accumulation without any major operational problems.

At 33 670 km, the engine was again dismantled, and comprehensive engine measurements were recorded (Appendix C).

A summary of the engine wear measurements is listed in Table 19. Most of the measurements showed acceptable engine wear and were within the manufacturer's specifications, except for the exhaust valve guides. The bottom portions of these guides showed a large degree of wear, but the top portion showed little, so that these guides became conical in shape. Because of the abnormal wear of the exhaust valve guides, a large amount

of carbon deposit was also found in the exhaust valve stem of cylinder No. 2 (Figure 16). All the four connecting rod bearings also showed a slight degree of wear, as indicted by the wear marks (Figure 17), but the dimensions were within the specification.

Other engine part measurements, such as piston ring gap, cam lift, and cylinder bore were all within the manufacturer's specifications and did not show any abnormal changes. The limited amount of engine wear is in close agreement with the low wear metal concentrations, as indicated by the used-oil analysis.

5.7/ Used-Oil Analysis

Table 20 shows the initial inspection properties of the three oil formulations used by the Ford Escort.

Table 21 shows the used-oil analysis results of the Ford Escort after completing the first segment of distance accumulations.

The interpretation of the oil analysis data is directed at three particular areas: oil condition, contamination, and engine wear.

One of the best indicators for the engine oil condition is an increase of viscosity, partly caused by the evaporation of lighter base oil fractions and the loss of volatile oil degradation products. The viscosity measurements at 40°C of the used-oil samples were within 0.5 to 1.0 centistokes (cSt) of the base oil. This change of oil viscosity was normal for the vehicle usage. The metal corrosion effect is best indicated by the total acid number (TAN) and total base number (TBN). The TAN increased by 0.5 to 1.5 numbers over the new oil, and the TBN decreased by about six numbers. This indicates that acids were being produced and neutralized in service. The reduction of TBN was higher than for a typical gasoline engine, but does not exceed an acceptable level.

The contamination of engine oil is best indicated by the fuel dilution test. The narrow boiling range of the methanol fuel poses oil dilution problems, particularly for cold-weather operations. However, the fuel

dilution test showed very low values and indicated fuel dilution was not a problem for the MTC methanol Escort when used for long distance accumulation.

Wear metal concentrations are expressed in parts per million (ppm) in the analysis and are generally used to judge the condition of engine components. Analysis of the type and levels of wear metals can be used to determine which engine components are wearing and if the level of wear is critical:

- The aluminum (Al) concentration was about average level, 20 ppm, which indicates that the methanol fuel did not cause excess corrosion in the intake manifold or cylinder head.

- The chromium (Cr) level was low and reflects the low wear level of the piston rings.

- The copper (Cu) level is associated with bearing wear and usually increases with vehicle-kilometres, but low Cu values indicate that the bearing wear was minimal.

- Iron (Fe) particles are products of cylinder bore wear. The iron level was about 30 to 50 ppm, which was lower than most engine values.

- The lead (Pb) level was about 50 ppm. This value is considered high for vehicle fuelling with methanol instead of unleaded fuel. This abnormal lead level is probably caused by the corrosion of the filler neck, which is made of terneplate -- steel covered with a lead/tin alloy commonly used for the construction of gasoline tanks.

Overall, most of the wear metal concentrations were low, with little deterioration in the oil quality. Combining this result with the engine component measurements confirms that the level of engine wear of this methanol vehicle is very low. This is mainly because the vehicle was mostly driven on the highway and, therefore, was not subjected to severe service conditions.

6/ CONCLUSIONS AND RECOMMENDATIONS

1/ The cold-starting performance of the test fuels was comparable or, in most cases, worse than the baseline M90. A new batch of test fuels could be formulated with higher volatility for further cold-start tests of the methanol vehicles.

2/ At a given vapour pressure, the three-component mixture containing methanol, DMM, and DME achieved lower starting temperatures than the two-component mixtures without DMM. The low lean flammability limit of DMM may be responsible.

3/ The formulated methanol fuels suffered about 7% loss of volatility during the six-month storage period and adversely affected the cold-starting performance of the test fuels.

4/ The methanol VW Golf showed a lower starting temperature limit than the Ford Escort. The main reason is the better design and the location of the heating element of the Golf, which significantly increases the temperature of the air-fuel mixtures before entering into the engine for starting.

5/ It is likely that the standard-size battery would not meet the demand at the lowest temperatures; consequently, larger battery capacity would be appropriate.

6/ The present cold-starting procedure often causes flooding in the spark plugs. A modified procedure is already used by Shell research and could be adopted by MTC for future testing.

7/ Initial engine damage was caused by preignition and the use of incorrect spark plugs. However, after this was remedied, the results of the used-oil analysis and the engine tear down inspection indicated that the methanol Escort generally has an acceptable engine wear level.

7/ REFERENCES

[1] Elliott, D. and Tsang, M., "Federal/Provincial Methanol Vehicle Test Program, Ontario Ministry of Transportation and Communications, Downsview, March 1983.

[2] Mitchell, D.K., "Straight Methanol and Vehicle Evaluation -- Phase 1; the Cold Weather Performance of a Variety of Methanol Fuel Blends," Report No. AF-84-03, prepared for the Transportation Energy Management Program, Ontario Ministry of Transportation and Communications, Ontario Ministry of Energy, Downsview, April 1984.

[3] Mitchell, D.K., "Straight Methanol and Vehicle Evaluation -- Phase 2; Durability of a Fleet of Methanol-Fuelled Vehicles," Report No. AF-85-03, prepared for the Transportation Energy Management Program, Ontario Ministry of Transportation and Communications, Ontario Ministry of Energy, Downsview, August 1985.

Table 1/ Physical and Chemical Properties of Methanol Derivatives

	Methanol	Dimethyl Ether (DME)	Dimethoxymethane (DMM)	Methyl Formate (MF)
Structure	CH_3-OH	CH_3-O-CH_3	CH_3-O-CH_2-O-CH_3	CH_3-O-CH=O
Molecular Weight (MW)	32	46	76	60
Density	0.793	(gas)	0.865	0.974
BP/°C	65°	- 23°	42°	31.5°
Latent Heat MJ/kg	1.226	0.492	0.349	0.490
Lower Heating Value (LHV)				
MJ/L	15.99	-	20.20	14.57
MJ/kg	20.16	31.72	23.35	14.96
Lean Flammability Limit % atm	0.067	0.03	0.016	0.0505
Vapour Pressure (VP)				
0°C, % atm	0.04	-	0.13	0.25
-20°C, % atm	0.01	1.2	0.45	0.09
Saturated Lean Flammability Limit Temperature, °C	9°C	very low	-36°C	-30°C

Table 2/ Test Fuel Properties

Composition by Weight					Vapour Pressure (kPa)	
Fuel	Methanol	DMM	DME	Gasoline	As Supplied	After 6-Month Storage
a	96.4	-	3.6	-	63.4	59
b	95.7	-	4.3	-	77.7	72
c	86.6	10.0	3.4	-	75.8	70
d(M90)	89.27	-	-	10.73	51*	-

*As supplied by Shell Canada Inc.

Table 3/ Factory Modifications to the Base Ford Escort for Methanol Fuel

Fuel System

- stainless steel fuel tank
- nickel-plated brass float and sending unit (in tank)
- nylon-coated fuel tank straps
- stainless steel fuel lines
- nickel-plated fuel pump
- new carburetor spacer, incorporating an electrical heating unit

Engine (1.6 L version)

- 11.8 to 1 compression ratio pistons
- one top piston ring, barrel-faced and hard-chromed
- head gasket with a stainless steel fire ring
- distributor with modified advance timing curve
- spark plug two heat range colder than the plugs used in the gasoline Escort

Table 4/ Chart Recorder Settings and Sensor Positions for Cold-Start Tests

Chan. No.	Function	Ford Escort		VW Golf	
		Position	Chart Setting	Position	Chart Setting
1	temperature	intake manifold 1	50 mV/cm	intake manifold 1	50 mV/cm
2	temperature	carburetor heater spacer	50 mV/cm	carburetor spacer	50 mV/cm
3	temperature	inlet air	50 mV/cm	inlet air	50 mV/cm
4	temperature	intake manifold 4	50 mV/cm	manifold heater	50 mV/cm
5	temperature	intake manifold 2	50 mV/cm	intake manifold 2	50 mV/cm
6	speed	engine rpm cranking	200 mV/cm	engine rpm cranking	200 mV/cm
7	speed	engine rpm	2 V/cm	engine rpm	2 V/cm

Table 5/ Variation of Cranking Speed (rpm) with Temperature

Ambient Temperature Range (°C)	Ford Escort		VW Golf
	Average Speed Without Auxiliary Battery (rpm)	Average Speed with Auxiliary Battery (rpm)	Average Speed (rpm)
4 to -3	310	340	290
-4 to -11	260	315	-
-12 to -20	100	300	260

Table 6/ Rate of Temperature Increase of Heaters

Ambient Temperature Range (°C)	Ford Escort		VW Golf	
	Rate of Rise of Temp (°C/s)	Maximum Temp (°C)	Rate of Rise of Temp (°C)	Maximum Temp (°C)
4 to -3	2.49	19.6	1.03	30.9
-4 to -11	2.16	17.4	0.94	28.3
-11 to -20	2.90	21.5	0.89	25.9

Table 7/ Average Maximum Temperature Reached in the Carburetor Spacer During Accelerator Depression (Ford Escort)

Ambient Temperature Range	Average Temperature on First Cranking (°C)	Average Temperature on Second Cranking (°C)
4 to -3	40.3	46.0
-4 to -11	32.4	26.4
-12 to -19	27.9	12.7

Table 8/ Minimum Vehicle Starting Temperatures

Fuel	a) 3.6% DME		b) 4.3% DME		c) 3.4% DME 10% DMM		d) 10% Gasoline	
Cranking Time	30 s	45 s	30 s	45 s	30 s	45 s	30 s	45 s
Temperatures, °C								
Ford Escort	-7.0	-10.2	-4	NA	-12.5	-16.5	-10.5	-14.0
Golf	-11.0	-13.5	-10.9	-13.5	-14.2	-16.5	-15.0	-18.0

Table 9/ Temperature Increase of the Intake Manifolds at the Start of Cranking for VW Golf

Ambient Temperature Range (°C)	Cylinder #1			Cylinder #2		
	Average Rate of Increase (°C/s)	Average Time for Temp Rise (s)	Average Maximum Temp (°C)	Average Rate of Increase (°C/s)	Average Time for Temp Rise (s)	Average Maximum Temp (°C)
4 to -3	2.18	1.75	3.82	1.55	2.85	4.43
-4 to -11	1.70	1.69	2.89	1.33	2.92	3.88
-12 to -20	1.14	3.8	4.34	1.28	4	5.13

Table 10/ Temperature of the Intake Manifold of Ford Escort Just Before the First Engine Firing

Fuel	Starting Temp (°C)	Ford Escort	
		Manifold #1 (°C)	Manifold #4 (°C)
a) 3.6 DME	-9	-3	-6
b) 4.3 DME	-8	-4	-7
c) 10 DMM 3.4 DME	-12	-8	-10
d) M90	-14	-11	-9

Table 11/ Temperature of the Intake Manifold of VW Golf Just Before the First Engine Firing

Fuel	Starting Temp (°C)	VW Golf	
		Manifold #1 (°C)	Manifold #2 (°C)
a) 3.6 DME	-9	0	1.5
b) 4.3 DME	-8	-0.5	1.2
d) M90	-19	2	8

Table 12/ Cold-Starting Results of VW Golf -- Fuel a): 3.6% DME

Ambient Temperature (°C)	Cranking Time (s)
-2	9.5
-3	9.0
-3	10
-5	7
-7	7.5
-7	12
-7	24
-8	70
-9	14
-9	17
-10	13
-11	71

Table 13/ Cold-Starting Results of VW Golf -- Fuel b): 4.3% DME

Ambient Temperature (°C)	Cranking Time (s)
-3	11.5
-5	9.0
-7	17.6
-9	17.4
-14	11.1
-19	70

Table 14/ Cold-Starting Results of VW Golf -- Fuel c): 10% DMM, 3.4% DME

Ambient Temperature (°C)	Cranking Time (s)
1	2
-2	5
-2	4.5
-5	9.5
-7	12
-11	18.5
-14	27
-16	45
-18	71

Table 15/ Cold-Starting Results of VW Golf -- Fuel d): M90

Ambient Temperature (°C)	Cranking Time (s)
4	2
-4	9
-5	10
-8	13
-13	20
-18	47
-21	62

Table 16/ Cold-Starting Results of Ford Escort -- Fuel a): 3.6% DME

Ambient Temperature (°C)	Cranking Time (s)
-4	8
-0	14.5
-1	10
-2	14
-3	11
-3	12
-3	14.5
-7	33
-9	44.5
-9	58
-11	54
-12	

Table 17/ Cold-Starting Results of Ford Escort -- Fuel c): 10% DMM, 3.4% DME

Ambient Temperature (°C)	Cranking Time (s)
+2	5.5
-1	1.6
-4	12
-5	10.5
-7	18.5
-12	31
-14	28
-14	37
-16	65

Table 18/ Cold-Starting Results of Ford Escort -- Fuel d): M90

Ambient Temperature (°C)	Cranking Time (s)
-1	8
-1	9
-1	11
-4	13
-6	14
-8	15
-8	16
-8	17
-11	22.5
-14	37
-18	47

Table 19/ Engine Inspections of Methanol Ford Escort at 33 670 km

Engine Wear	Cyl. #1	Cyl. #2	Cyl. #3	Cyl. #4	Specifications (mm)
Cylinder Wear					
Cyl. Bore Wear (mm)					
Top of Travel	0.01	0.02	0.01	0.00	
Piston Ring Gap (mm)					
Top Ring	1.12	1.12	1.12	1.12	0.4 - 1.4
2nd Ring	0.42	0.475	0.48	0.48	0.3 - 0.5
Oil Ring	0.47	0.49	0.49	0.47	0.3 - 0.5
Piston Ring Groove Width (mm)					
Top Groove	1.65	1.65	1.65	1.65	1.64 - 1.660
2nd Groove	2.05	2.05	2.05	2.05	2.038 - 2.062
Oil Groove	4.02	4.02	4.02	4.02	4.032 - 4.008
Intake Valve Guide Bottom (mm)	8.08	8.08	8.08	8.08	8.063 to 8.094
Exhaust Valve Guide Bottom (mm)	8.16	8.14	8.25	8.15	
Pits on Valve Tappets	Nil	Yes	Nil	Nil	
Deposits on Valve Stem	Nil	Yes	Yes	Nil	
Intake Camshaft Lift (mm)	5.77	5.78	5.79	5.79	5.678 - 5.805
Exhaust Camshaft Lift (mm)	5.78	5.78	5.78	5.78	5.678 - 5.805

Table 20/ Lubricant Specifications

	Oil Type		
Components	Ford Fac. Fill	Shell 10W20	Shell 15W30
Base Oil	✓	✓	✓
Synthetic Oil		✓	✓
Additive Package	✓	✓	✓
Properties			
Viscosity @ 40°C, cSt	81.4	52.4	77.6
Viscosity @ 100°C, cSt	10.2	8.3	10.8
Pour Point, °C	-36	-42	-42
Density, kg/L	0.898	0.890	0.893
Sulphated ash, % by mass	2.81	2.88	2.89
Phosphorus, % by mass	0.15	0.16	0.16
Magnesium, mg/kg	28	24	24
Zinc, % by mass	0.18	0.19	0.19
Calcium, % by mass	0.73	0.77	0.76
TANe, D-664 mgKOH/g	2.3	2.4	2.3
TBNe, D-664 mgKOH/g	12.6	12.4	12.8
TBNe, D-2896 mgKOH/g	16.7	16.6	16.8

Table 21/ Methanol Vehicle -- Used-Oil Analysis

Car No. MTC 117

Oil Grade	FAC FIL 30	10W20	10W20	15W30	15W30	15W30	15W30	15W30	15W30	15W30	15W30
km	6164	7881	9522	12 145	13 908	15 495	17 147	18 652	20 210	22 090	23 778
Date (Oil Change)	May/84			July/84			Aug./84			Oct./84	
TANe mgKOH/g D-664	3.07			3.35			3.92			2.81	
TBNE mgKOH/g D-2896	16.4						11.9			9.83	
TBNe mgKOH/g D-664							11.5			5.59	
Fuel Dilution D-322	-						0.0			0.0	
Visc. @ 100°C	9.40			9.97			10.31			10.04	
Pentane Insol. D-893	0.41			0.049			0.086			0.371	
Al	18.0	8.8	14.0	23.8	11.6	13.4	17.4	8.7	13.4	18.1	9.6
Cr	7.4	0.20	0.3	1.0	0.2	1.0	1.4	0.04	0.2	0.4	0.08
Cu	31.2	2.5	4.0	38.9	6.9	5.6	6.8	2.1	4.3	15.9	4.1
Fe	57.1	17.3	31.4	52.2	25.8	34.3	42.8	15.6	29.4	40.1	22.0
Pb	121	51.7	78.7	350	43.3	40.7	51.9	19.6	39.3	63.9	126
Si	60.0	10.5	11.7	31.3	11.21	9.7	14.7	7.8	11.3	11.4	10.9
Pour Point, °C	-39										
Flash Point, °C	220										
Infrared Scan	done			done						done	
Comments	(drain)			(drain) (small sample)			(drain)			(drain)	

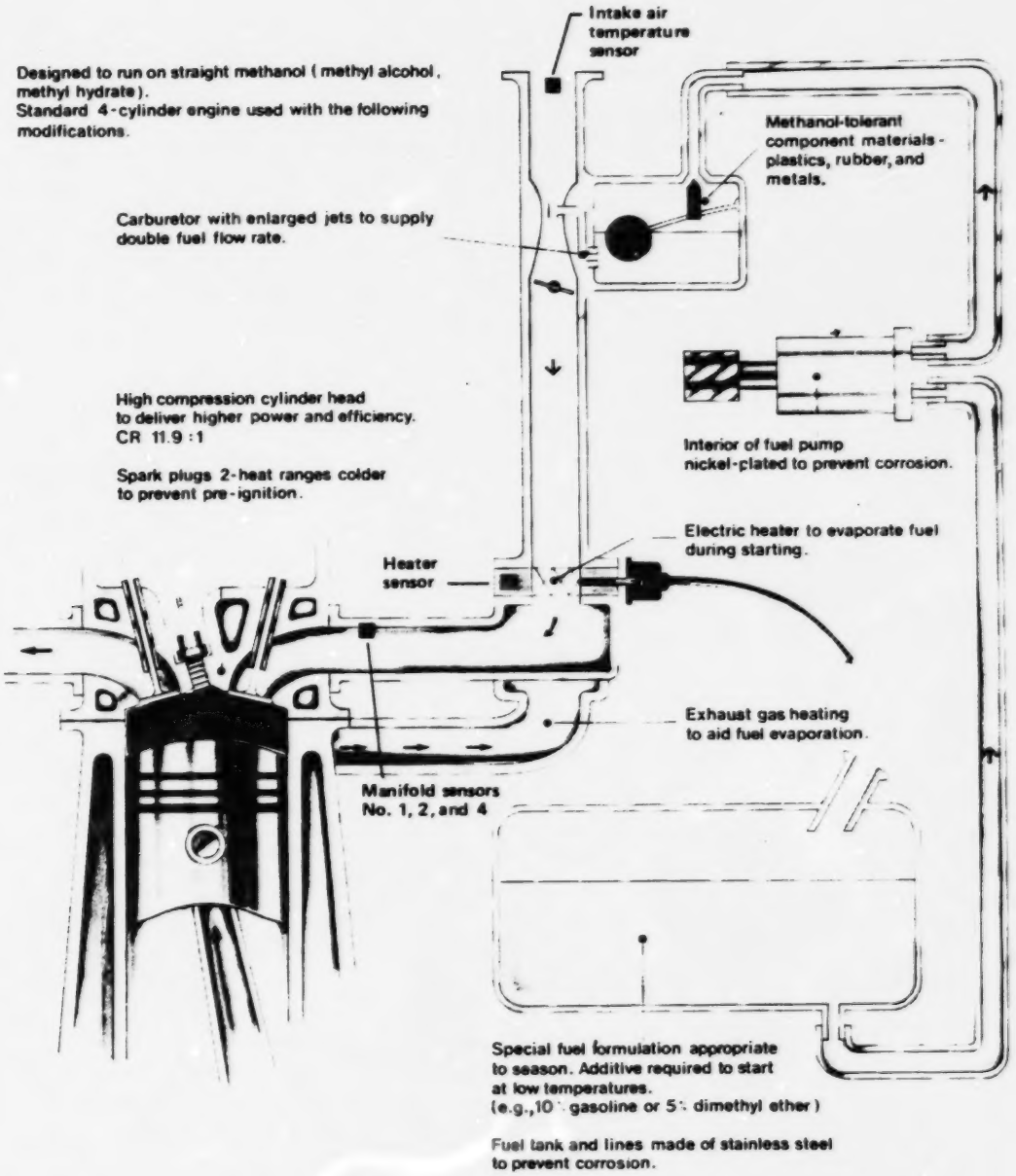

Designed to run on straight methanol (methyl alcohol, methyl hydrate).
Standard 4-cylinder engine used with the following modifications.
Intake air temperature sensor
Methanol-tolerant component materials - plastics, rubber, and metals.
Carburetor with enlarged jets to supply double fuel flow rate.
High compression cylinder head to deliver higher power and efficiency. CR 11.9 :1
Spark plugs 2-heat ranges colder to prevent pre-ignition.
Interior of fuel pump nickel-plated to prevent corrosion.
Electric heater to evaporate fuel during starting.
Heater sensor
Exhaust gas heating to aid fuel evaporation.
Manifold sensors No. 1, 2, and 4
Special fuel formulation appropriate to season. Additive required to start at low temperatures.
(e.g.,10 % gasoline or 5 % dimethyl ether)
Fuel tank and lines made of stainless steel to prevent corrosion.

Figure 1/ Positions of Thermocouples in the Ford Escort

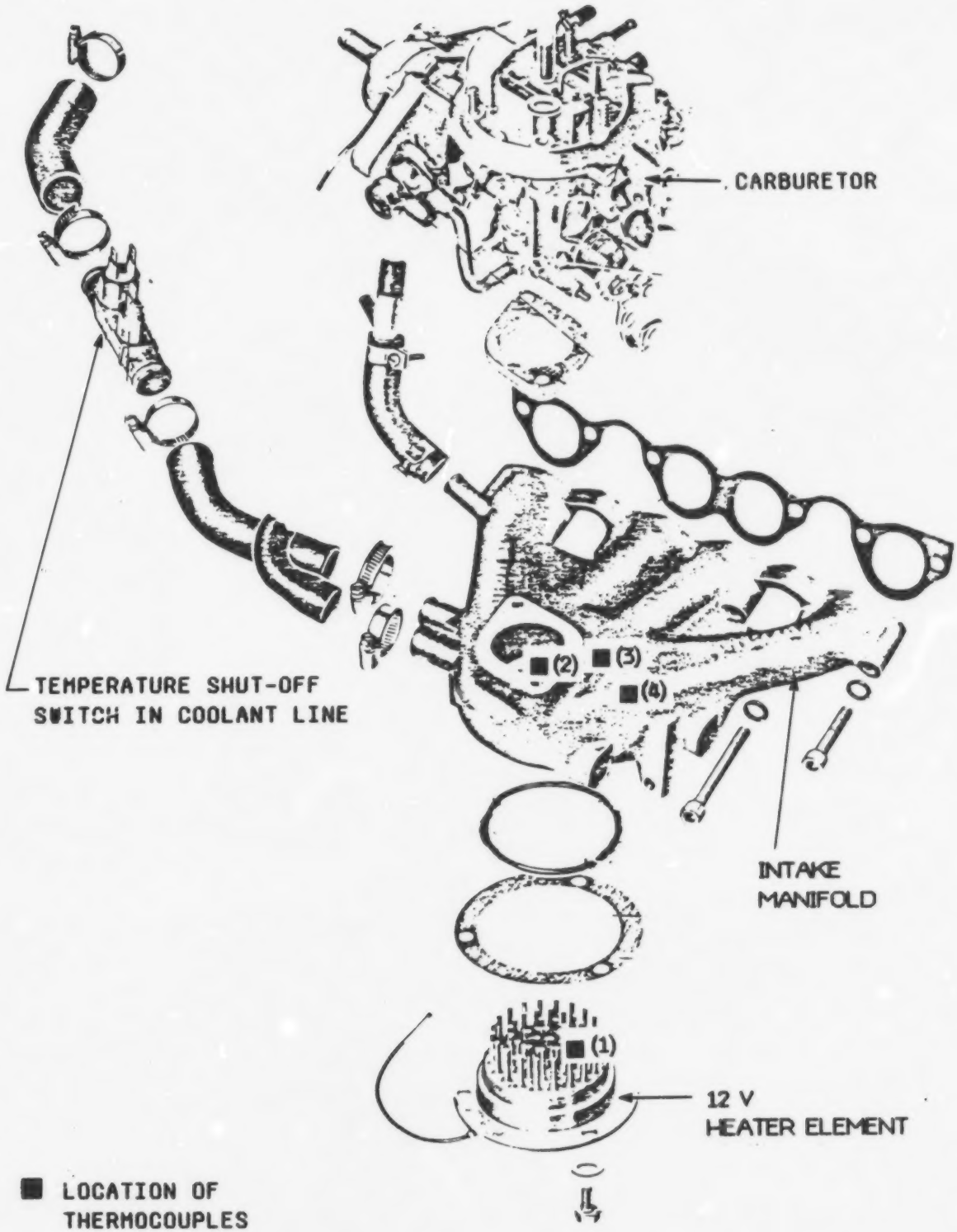


Figure 2/ Intake Manifold Details and Thermocouple Locations of VW Golf

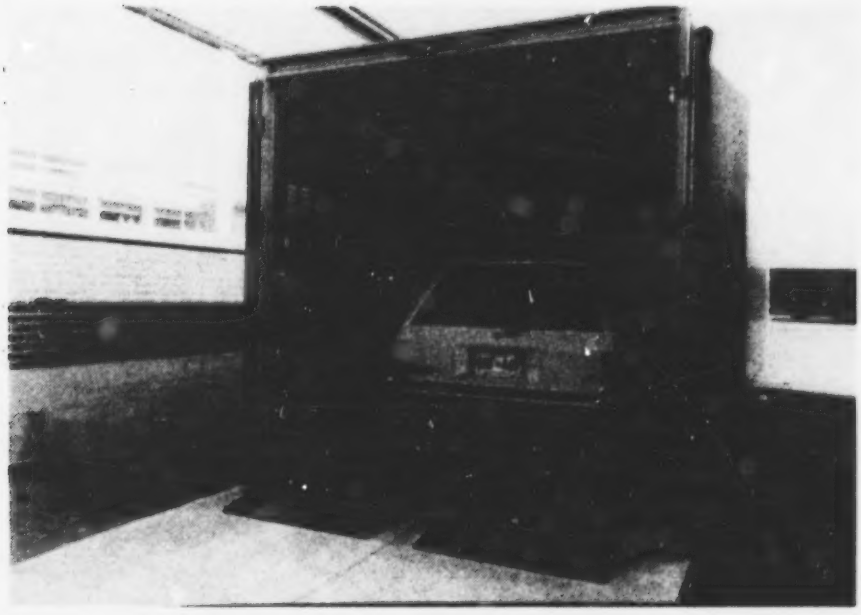
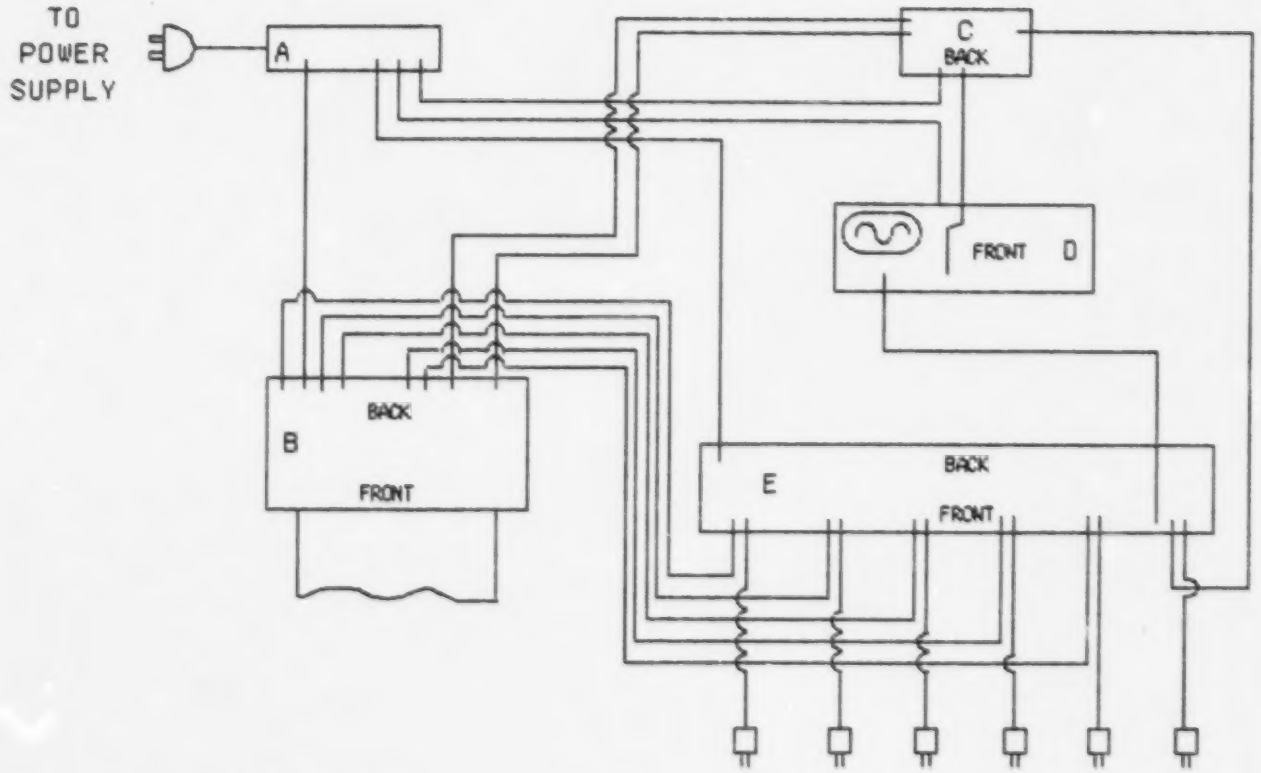


Figure 3/ Cold-Start Test Trailer

Figure 4/ Auxiliary Tank for Test Fuels Connected to VW Golf



A - HAMMOND "POWER BAR"
B - MFE 1800, 8-CHANNEL CHART RECORDER
C - POTENTIOMETER
D - TEKTRONIX TM515 WITH SC502 OSCILLOSCOPE
E - SIGNAL CONDITIONING AMPLIFIERS

Figure 5/ Instrumentation Layout

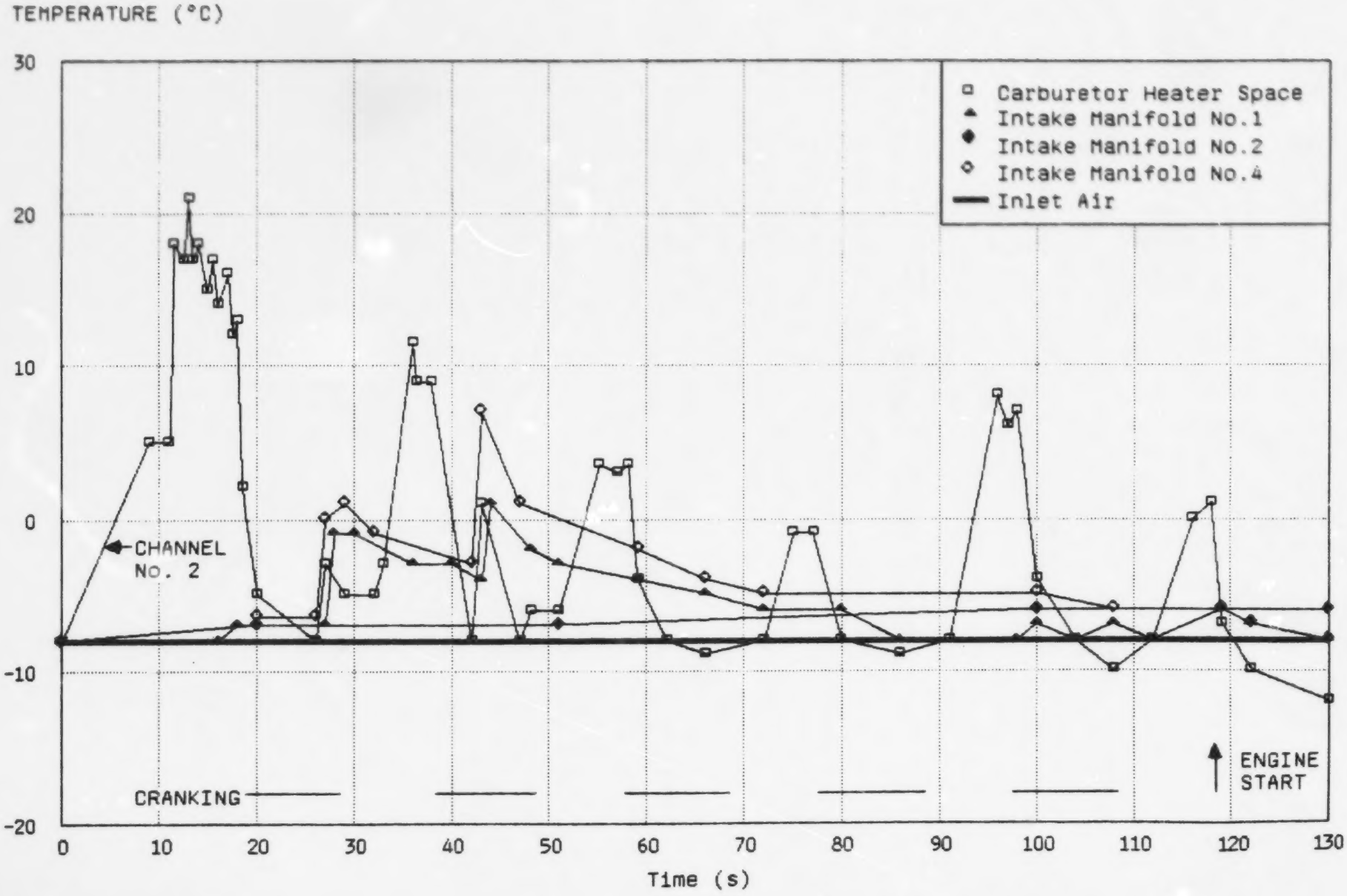


Figure 6/ Temperature Profile of the Intake System of Escort (Fuel, M90; Temp, -8°C)

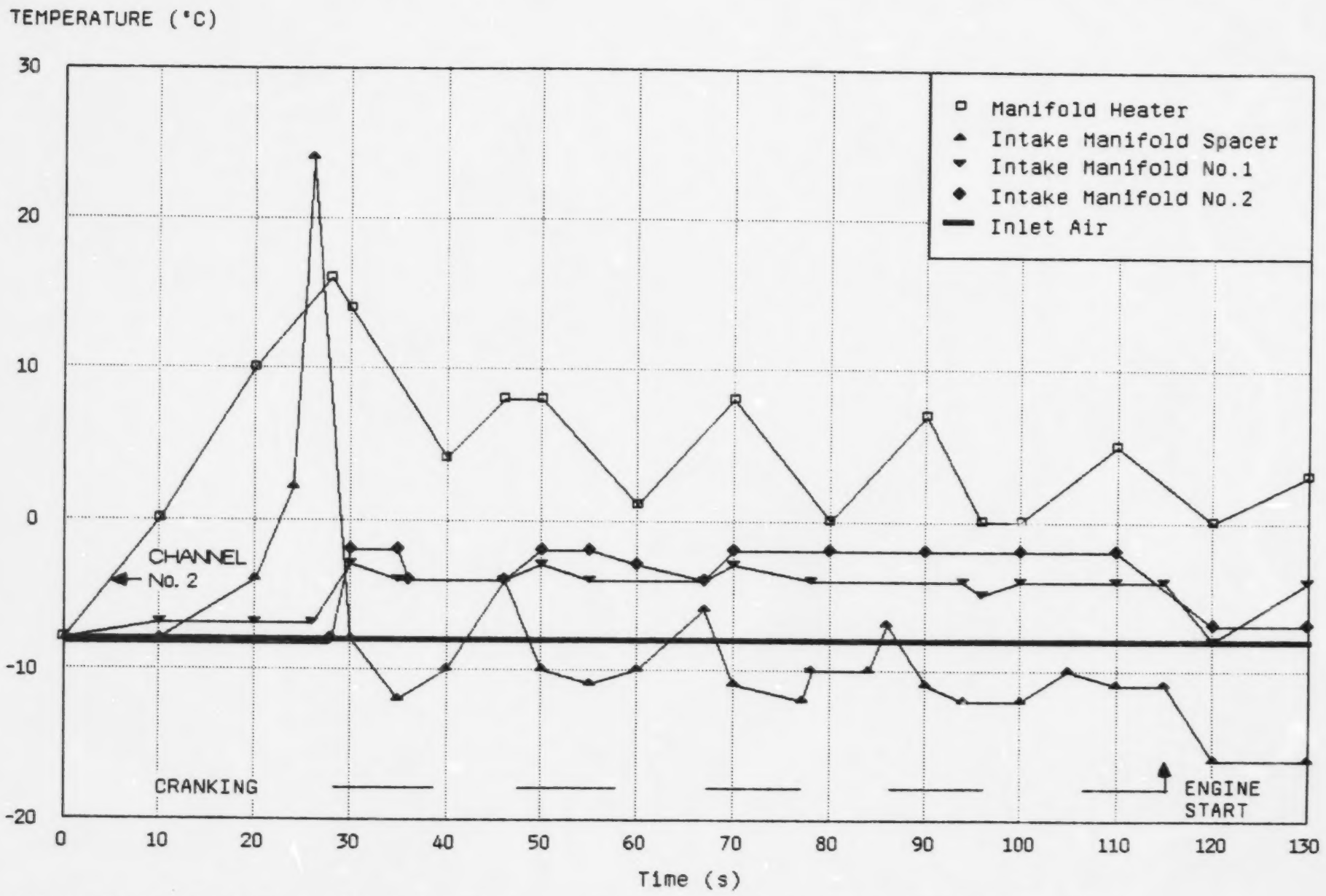


Figure 7/ Temperature Profile of the Intake System of VW Golf (Fuel, M90; Temp, -8°C)

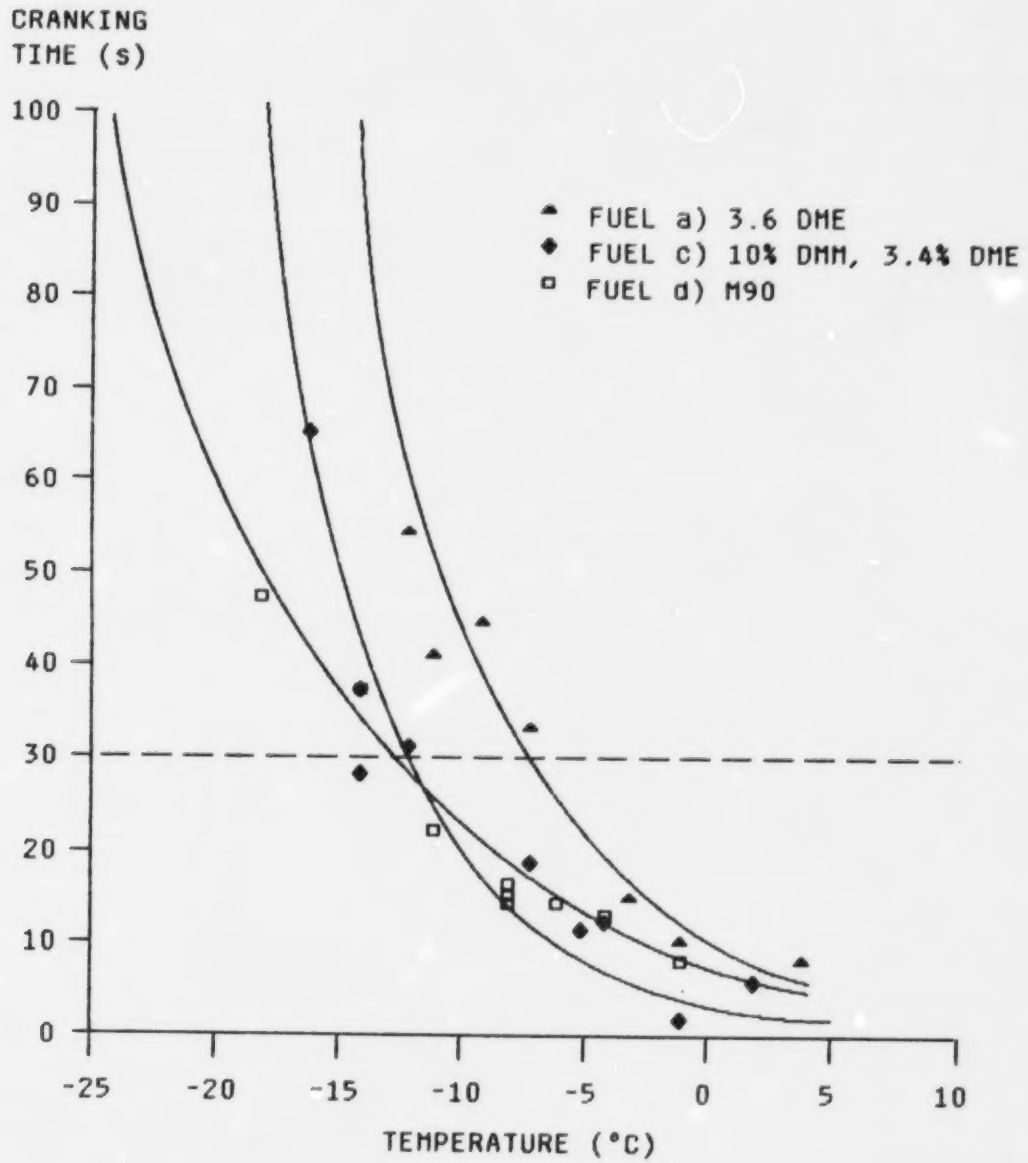


Figure 8/ Cranking Time vs. Cold-Starting Temperature for Ford Escort

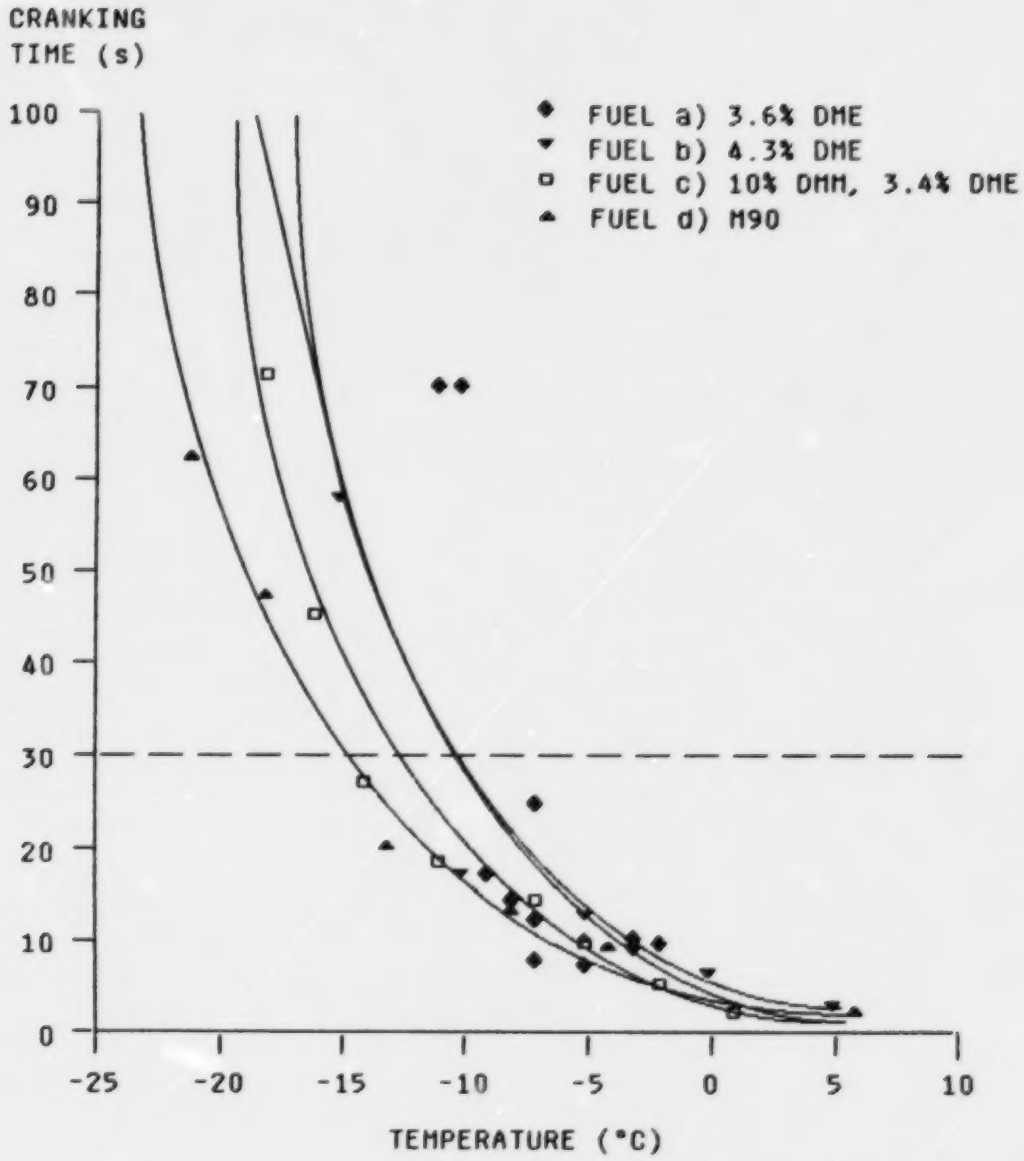
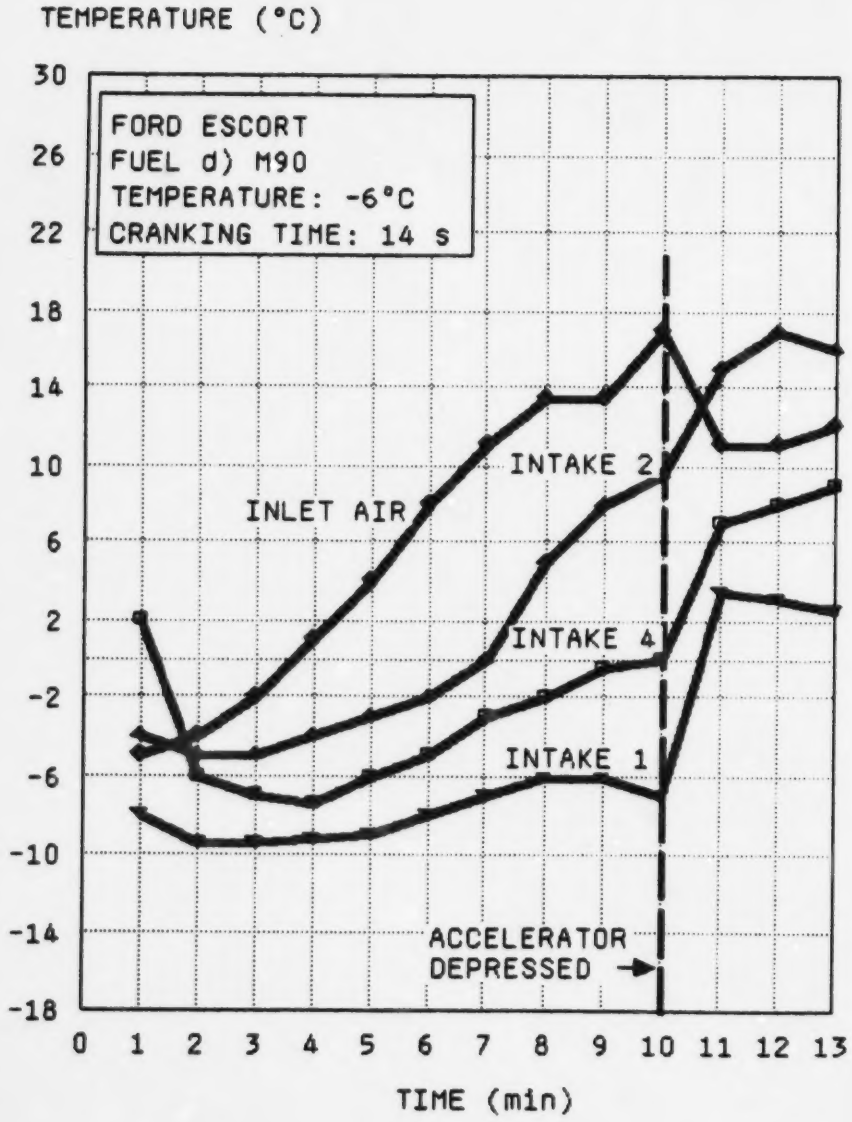


Figure 9/ Cranking Time vs. Cold-Starting Temperature for VW Golf



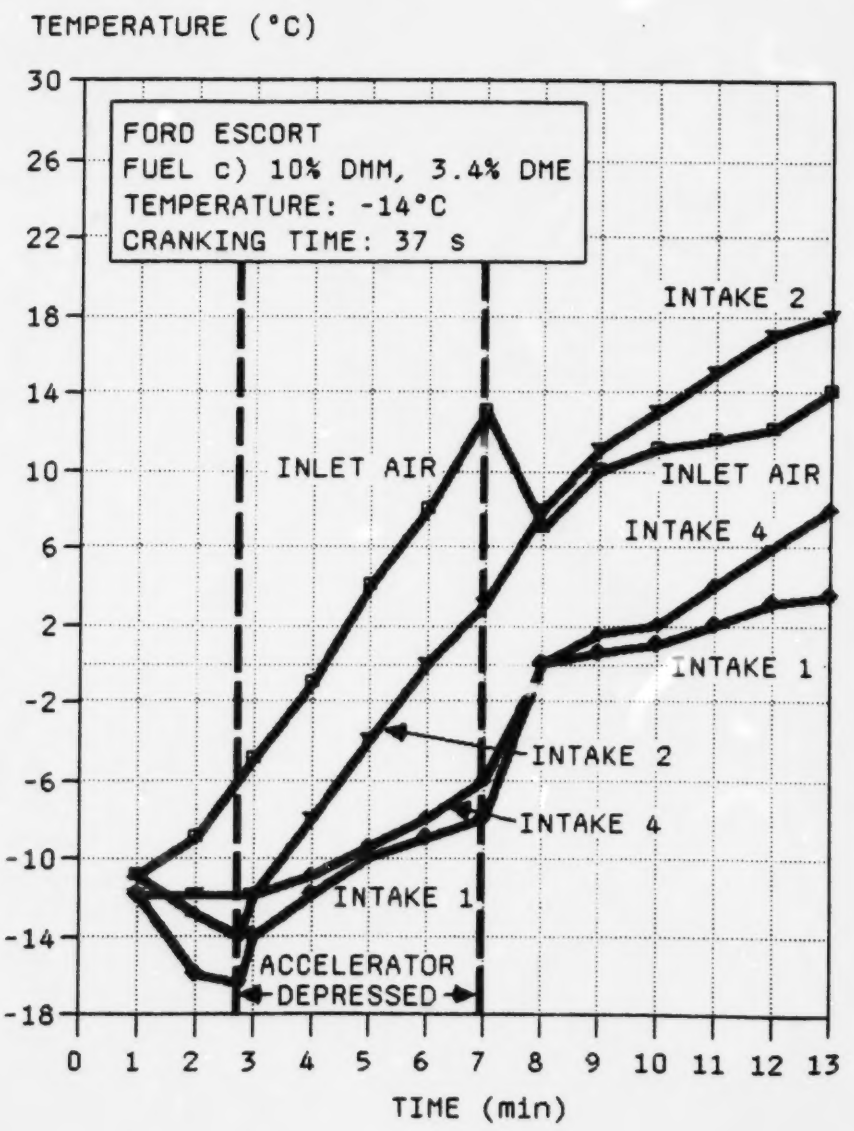
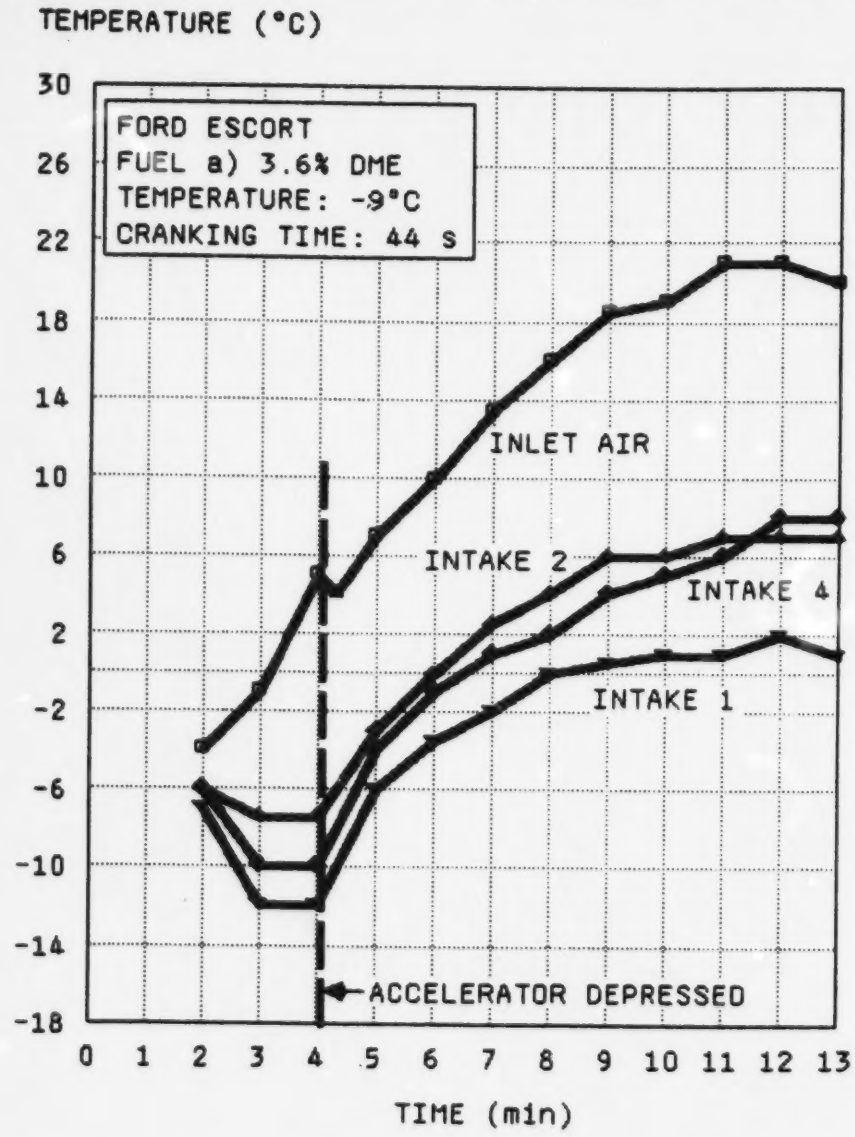


Figure 10/ Manifold Temperature During the Warm-up Period -- Ford Escort



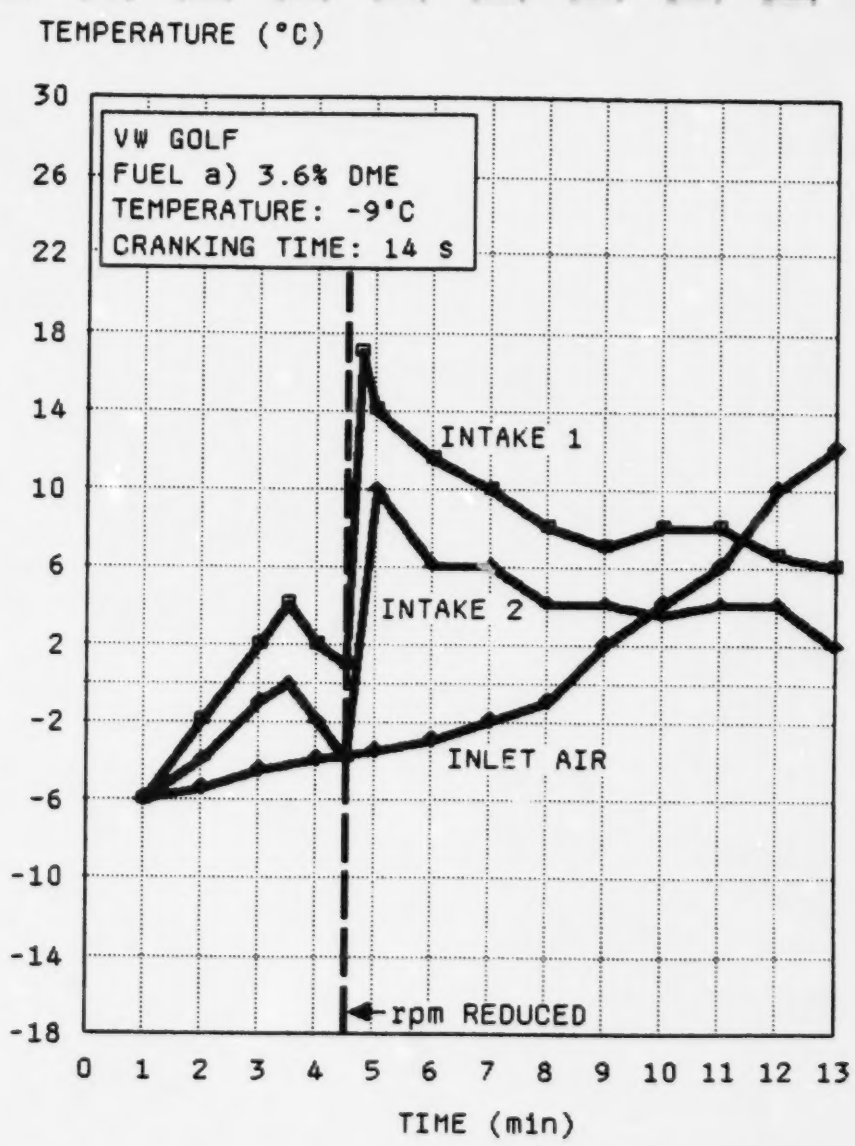
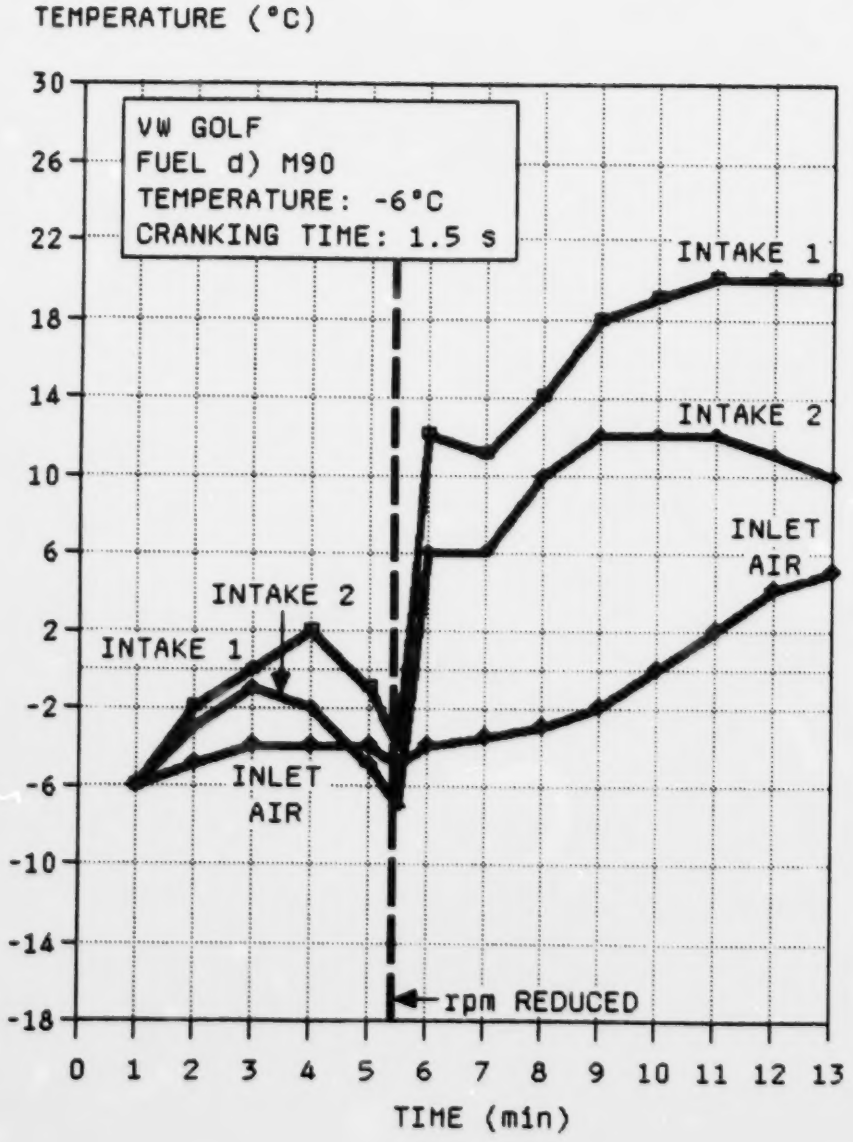


Figure 11/ Manifold Temperature During the Warm-up Period -- Ford Escort



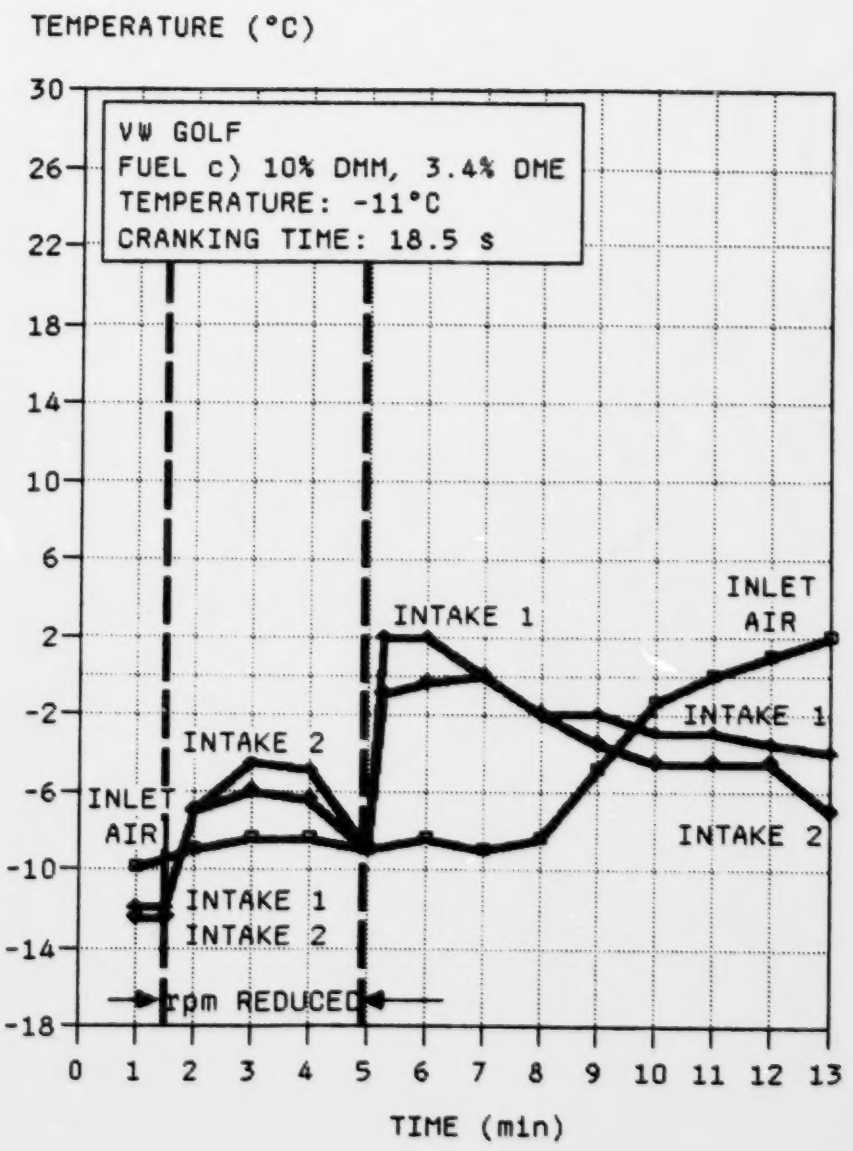


Figure 12/ Manifold Temperature During the Warm-up Period -- VW Golf

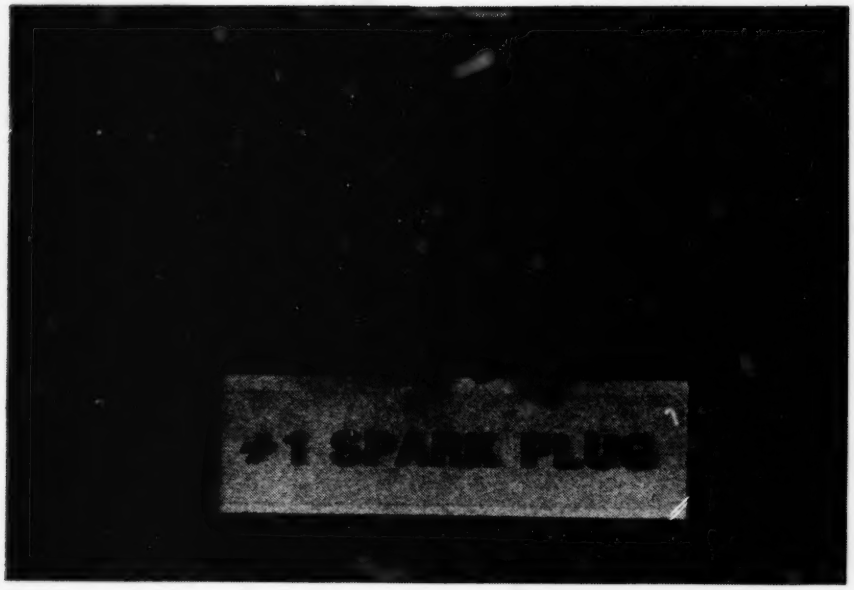


Figure 13/ Burned Spark Plug -- Ford Escort

Figure 14/ Deterioration of Intake Valves --
Ford Escort

Figure 15/ Carbon Deposits on Intake Valve -- Ford Escort

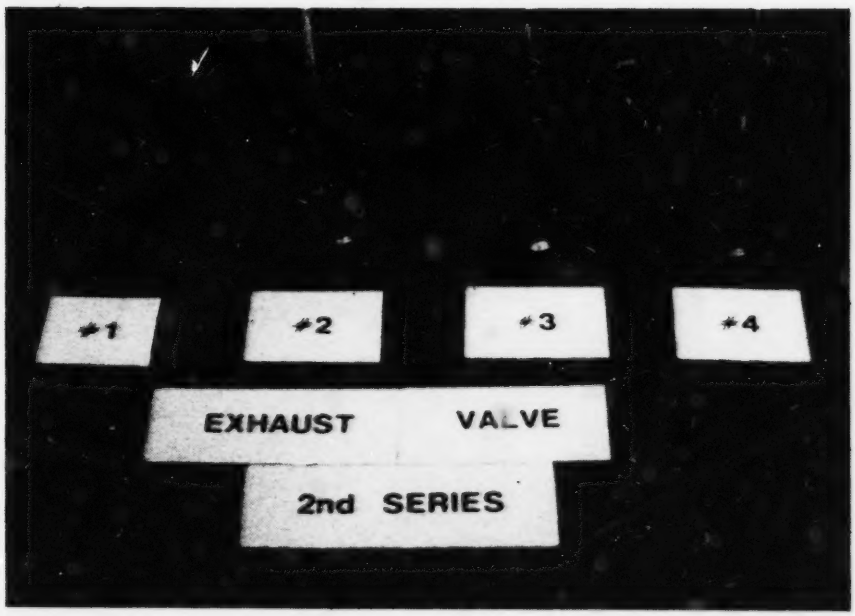


Figure 16/ Carbon Deposits on the Exhaust Valve of Number 2 Cylinder -- Ford Escort

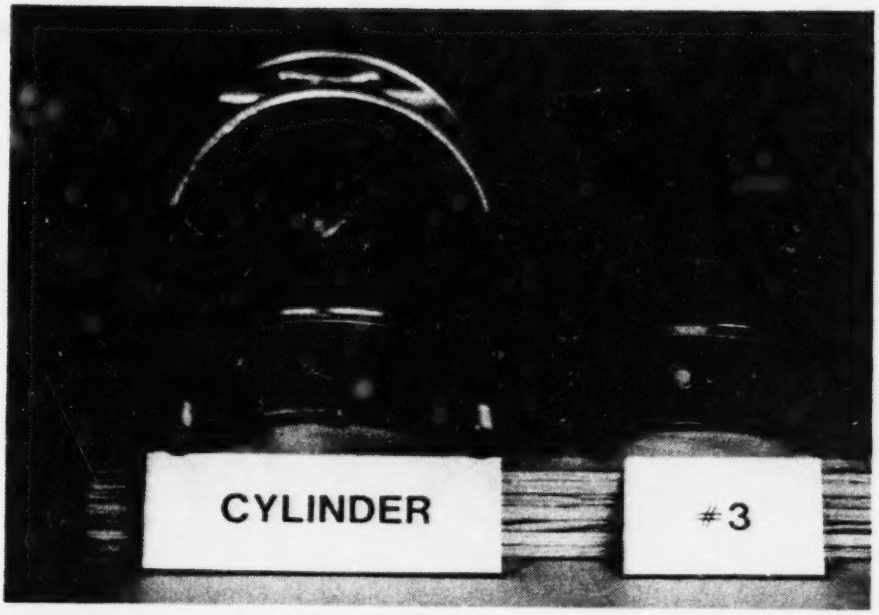


Figure 17/ Wear Marks of Connecting Rod Bearing -- Ford Escort

APPENDICES

APPENDIX A/ CARBURETOR HEATER TEST

A.1/ Ford Escort, Vehicle No. 83-117-001

The main induction system modification for the Escort is a small electric heater (early fuel evaporator [EFE]) installed between the carburetor and the intake manifold. This heater is designed to supply some initial heat to assist vaporization of the methanol fuel during cold-weather starting. The heater is activated by the ignition switch and stays on for approximately 5 min until the engine warms up and shuts it off automatically.

On December 13, 1983 measurements were taken by Technology Services Office staff to find out the power draw of the heater under actual running conditions. The test method used was simply to connect an ammeter into the heater power line and record the current flow during vehicle starting and warm-up.

A.1.1/ Results

As the ignition is turned on (engine not started), the heater draws about 9.4 A. This drops off immediately to approximately 4.5 A after 10 s and keeps falling steadily to 1 A after the first minute.

The car was then started and immediately the amperage climbed back up to approximately 9.5 to 9.0 A, where it levelled off until the heater automatically shut off when the vehicle's engine warmed up (Table A.1 and Figure A.1).

A.1.2/ Discussion

The cause of the rapid decline in power consumption during the first minute while the key was on but the engine not yet started is probably due to the temperature coefficient of resistance of the ceramic heater element. Increase in temperature will increase the resistance and, therefore, lower the current draw. This was shown when after about 55 s the accelerator was pumped once to provide a spray of methanol fuel through the carburetor and onto the heater. The heater was immediately

cooled by the methanol and resulted in the current draw jumping back up to 9.5 A. This same effect of a high current jump when methanol fuel vapour is flowing through the heater is seen when the vehicle is started. The current rises to about 9.5 A from 1 A and then steadies down to 8.6 A during the warm-up period.

A.2/ VW Golf, Vehicle No. 81-576-000

The intake manifold of the VW Golf has been redesigned to provide a heat exchanger, supplied by the engine coolant system, and an electric heater. The heater is activated through the ignition switch and stays on until the vehicle's cooling system reaches approximately 78°C. Initial tests on the manifold heater combination were carried out before installation on the vehicle to ascertain its heating ability and power requirements.

A.2.1/ Instrumentation

To measure the heating ability of the elements, copper-constantan thermocouples were attached to the manifold at the following locations, as shown in Figure 2:

- in the coolant of the manifold water jacket,
- two locations on the outside of the manifold on the opposite side from the heater element,
- on the heater element prongs, and
- at the exit of manifold ports No. 1 and 2.

The thermocouples were attached through a rotary switch box to a digital potentiometer for quick readout.

A.2.2/ Test Method

All tests were done with the manifold water jacket filled with tap water. Under normal operating conditions, the vehicle coolant would be circulating through the manifold. A fully charged 12 V car battery was used, and tests were conducted at room temperature.

The primary set of tests was to determine if the heating element did, indeed, heat the air as it passed through the manifold. Air under pressure was directed through the manifold to simulate the airflow while the car is starting and idling. Temperature time measurements on the manifold and in the air stream were taken at various flow rates.

The current from the vehicle's electrical system was determined by use of a standard ammeter.

The temperature-sensitive switch, which is installed in the vehicle's cooling system, was tested to ascertain the temperature the coolant must reach before it shuts the heater element off.

A.2.3/ Results

Temperature/time test results are given in Tables A.2 and A.3. Thermocouple readings indicate the heater element prongs reach their maximum temperature in just over a minute. The steady-state temperature of the prongs depends on the airflow through the manifold and is shown in Figure A.2.

The ability of the heater element to warm the air-fuel mixture as it passes through the manifold was assessed by measuring the temperature difference of the air going into and out of the manifold at varying flow rates.

The results, as plotted in Figure A.3, indicate the air temperature could rise as much as 14°C at engine cranking speed. With an engine idle speed of 1500 rpm, the air temperature rise through the manifold is approximately 10°C. It must be noted, however, that actual on-vehicle test results may show less of a temperature rise because of the methanol fuel vapour present. The bench tests reported here only used dry air and not an air-methanol mixture.

Power required for the heater was measured at approximately 19 to 20 A at operating temperature, as shown in Figure A.4. Higher currents will occur momentarily before the elements warms up.

The results from the thermocouples installed on the outside of the manifold casing and in the water jacket coolant indicate that the heat transferred to the airflow through the body of the manifold is not significant.

A.2.4/ Summary

- The small electric heater installed in the intake manifold increases the airflow temperature 10 to 14°C at engine starting and idle speeds.

- The heater element draws relatively heavy current (18 to 20 A) until it is automatically switched off when the vehicle's coolant system reaches approximately 78°C.

Table A.1/ Ford Escort Intake Manifold Heater Results

TIME (s)	Test 1 (A, dc)	Test 2 (A, dc)
0	CAR STARTED	9.38 IGNITION ON
10		4.50
20		1.69
30	9.4	1.19
40		1.01
50		0.95
60		9.60 CAR STARTED
90		8.82
120	8.75	8.65
150	8.74	8.65
180	8.72	8.61
210	8.73	8.60
240	8.70	9.56 CHOKE OFF
295	HEATER AUTO. SHUTOFF	9.60 HEATER AUTO. SHUTOFF

NOTE - BATTERY FULLY CHARGED DEC. 13, 1983

Table A.2/ VW Golf Intake Manifold -- Heater Element Prong Temperature at Varying Airflows

TIME (s)	AIRFLOW (ft^3/s)								
	0	0	2.4	5.0	5.8	9.0	10.2	20.8	28.3
0	18	21	22	21	21		21	23	23
10	31	35	31		30		31		
20	56	57	49		46		45		45
30	70	71	60		52		51		
40	79	79	65	65	63	59			50
50	83	83	69						
60	86	86	70		67	61		58	50
70	89	90	72	69					
80	90	90	72		69	62	56	58	50
90	91	90	73						
100	92	90	75		69	62	56	59	51
110	92	92							
120	92	92			70	62			52
130							59	59	
140				74					
160				74			59	59	
180				74	72	62			52
240				74		63	59	59	

NOTE: • AIR INTAKE TEMPERATURE 21-22°C
• WATER JACKET FULL, TEMPERATURE 21°C TO START
• BATTERY CHARGED TO MINIMUM 12.5 V

Table A.3/ VW Golf Intake Manifold -- Air Temperature Out of Manifold at Varying Airflow Rates with Heater Element On

TIME (s)	AIRFLOW (ft^3/s)						
	2.4	5.0	5.8	9.0	10.2	20.8	28.3
0	22	21	21	21	22	21	21
10	25	22	23	23	23	22	22
20	28	24	25	25	24	24	23
30	30	25	26	25	25	25	
40	32	26	27	26	26	25	24
50	33		27				
60	35	27	27	27	27	26	24
70	35	27					
80	35	27	28	27	27	26	25
90	35	28		27			
100	36		28	27	27	26	25
110		28					
120		28	28	27	28	26	25
180		29	29	27	28	27	25

NOTE: • AIR INTAKE TEMPERATURE 21-22°C
• WATER JACKET FULL, TEMPERATURE 21°C TO START
• BATTERY CHARGED TO MINIMUM 12.5 V

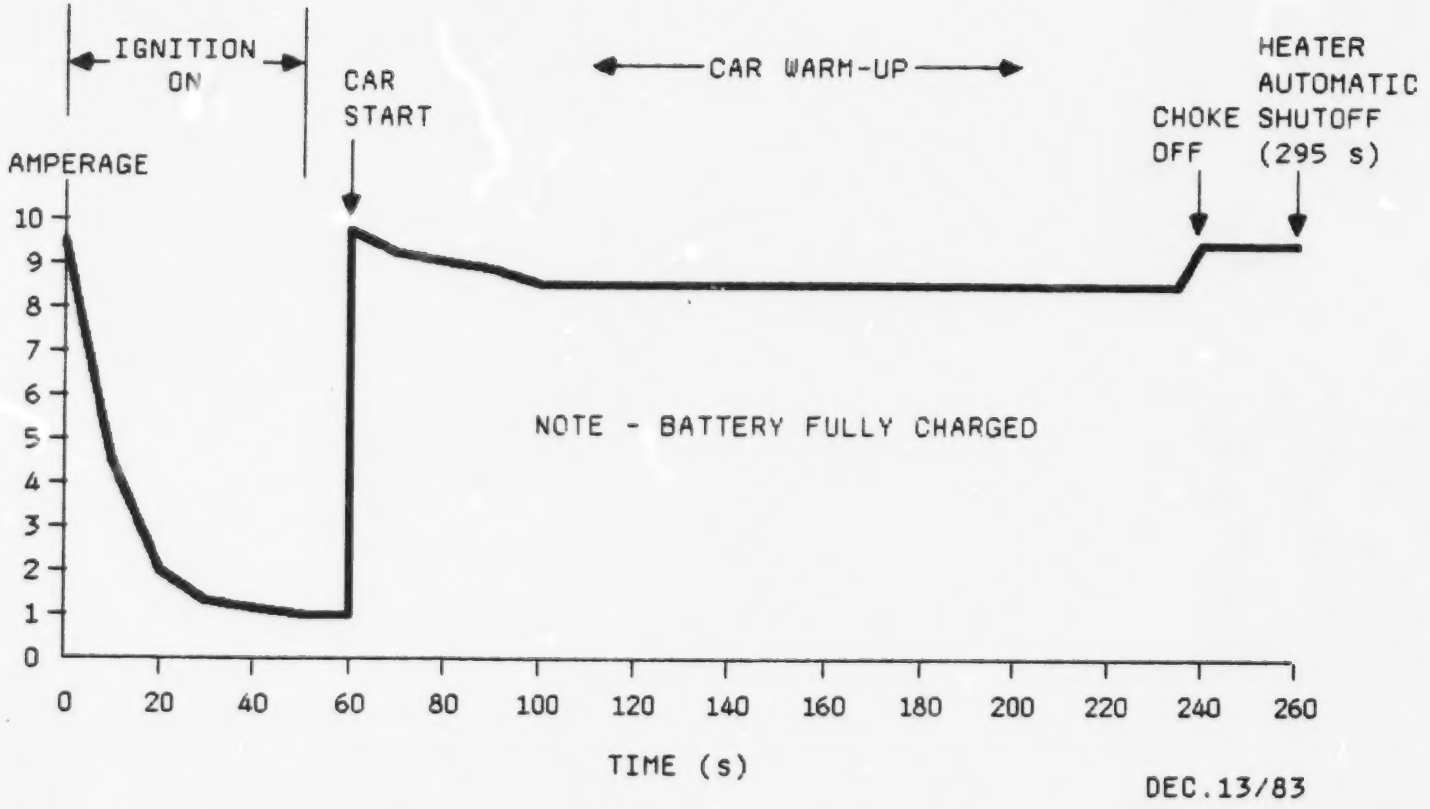


Figure A.1/ Ford Escort Manifold Heater Test

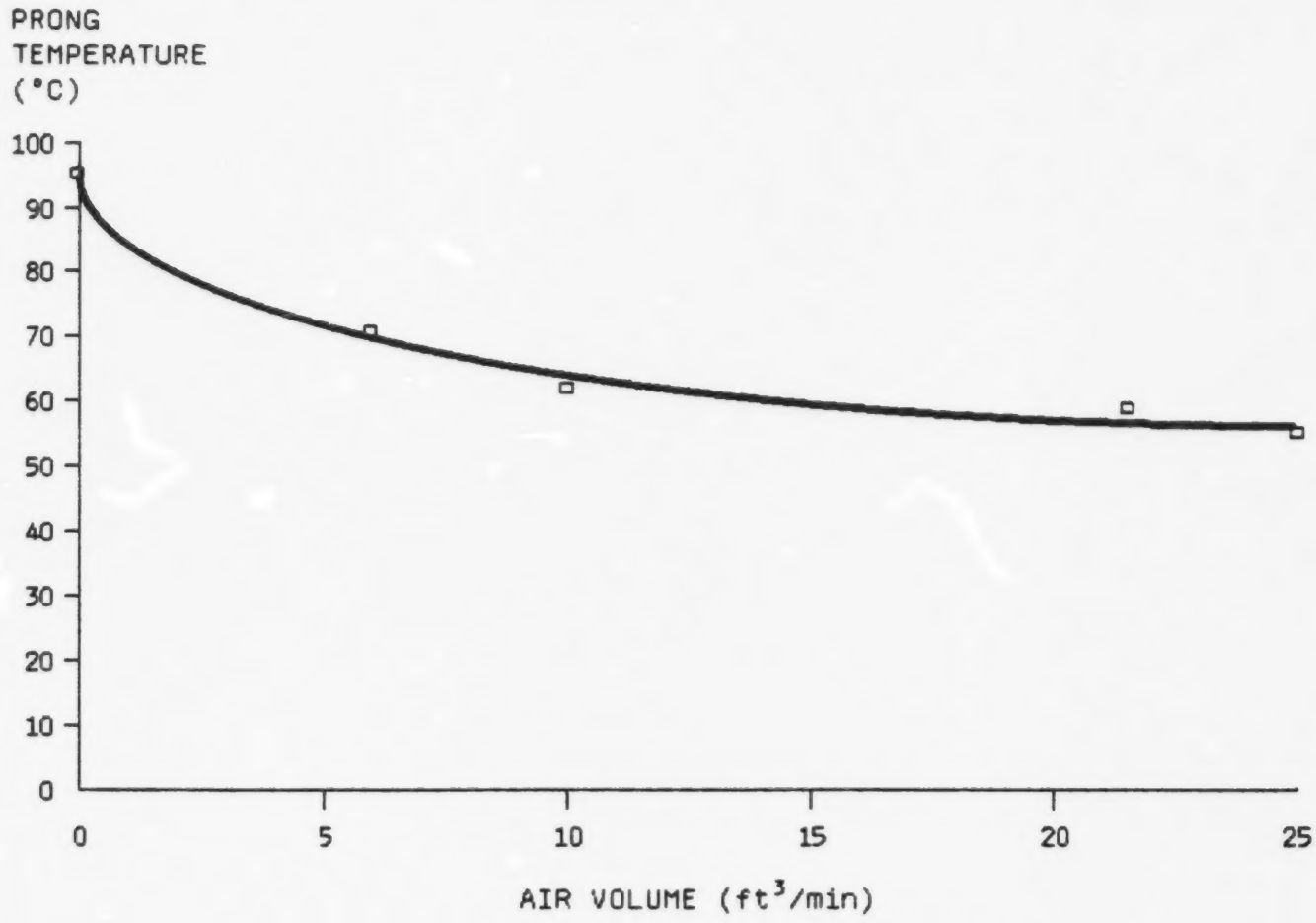
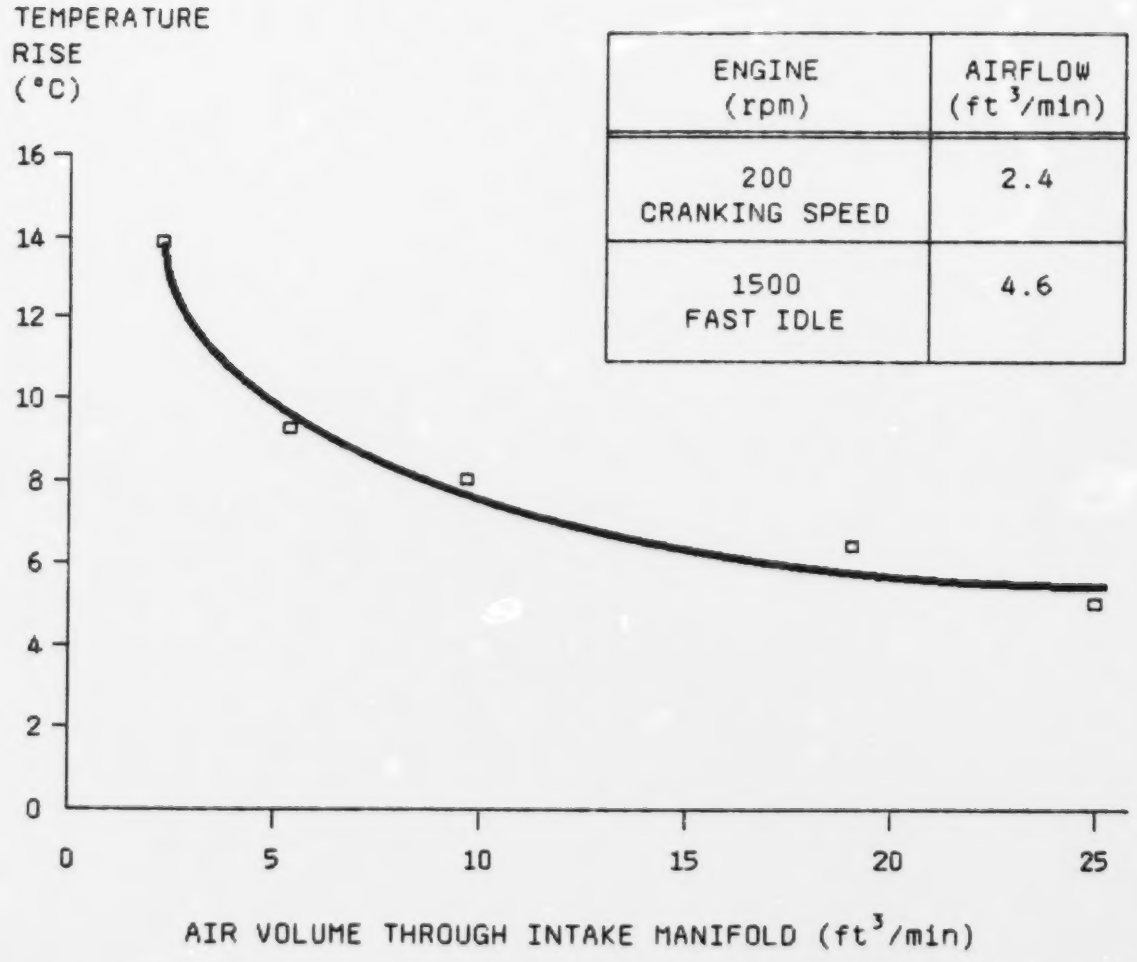


Figure A.2/ VW Golf Intake Manifold -- Heater Element Prong Temperature at Varying Airflows



ENGINE (rpm)	AIRFLOW (ft^3/min)
200 CRANKING SPEED	2.4
1500 FAST IDLE	4.6

Figure A.3/ VW Golf Intake Manifold -- Air Temperature Rise Through the the Intake Manifold with the Heater Element On at Varying Airflow Rates

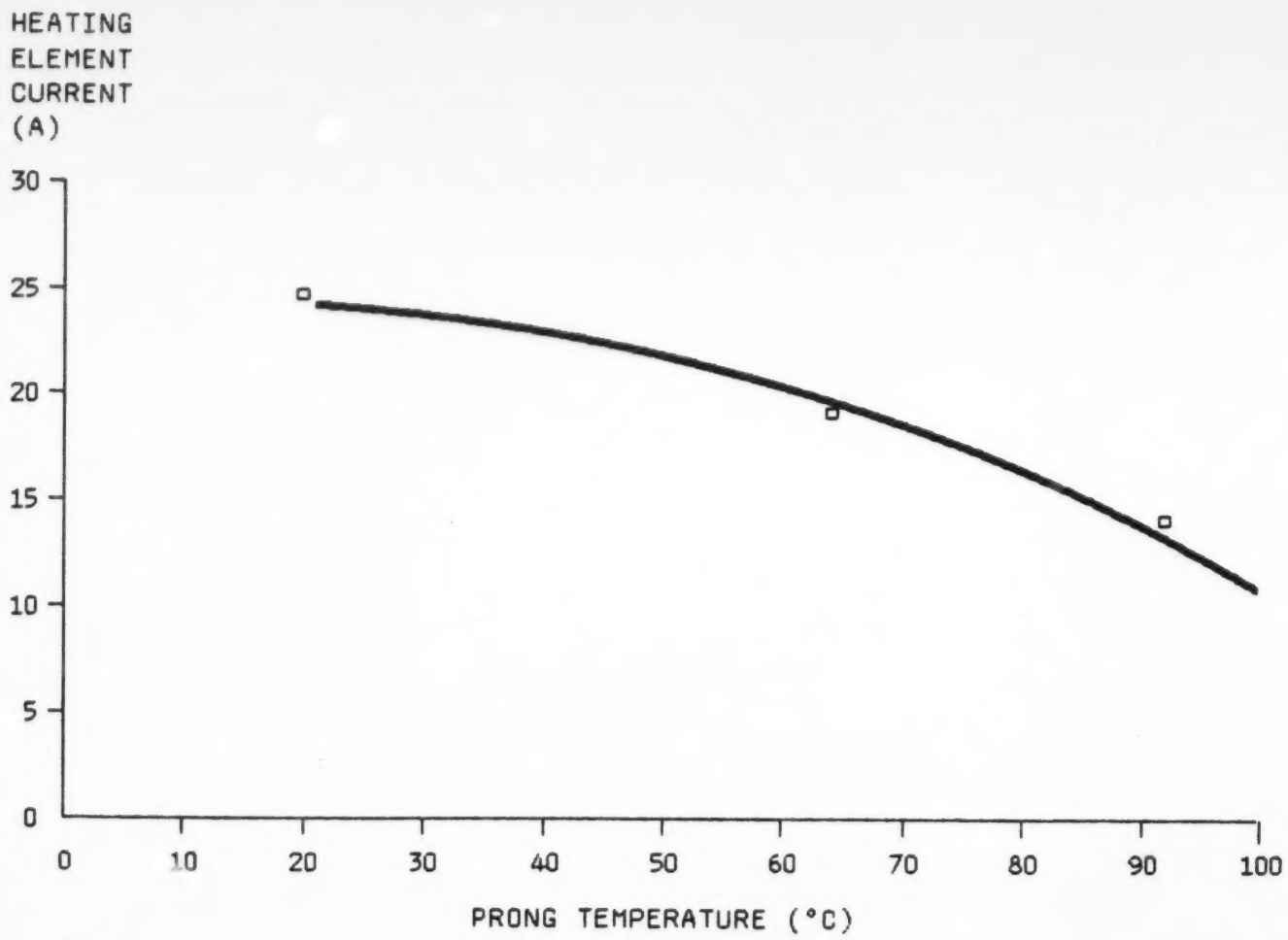


Figure A.4/ VW Golf Intake Manifold -- Current Drawn by Heating Element at Varying Prong Temperatures

APPENDIX B/ COLD-START PROCEDURE OF METHANOL VEHICLES

Cold-Start Procedure for VW Golf

1/ Pull the choke all the way out.
2/ Ignition switch on.
3/ Wait 25 s.
4/ Depress pedal 6 times.
5/ Crank for 10 s -- foot off accelerator.
6/ Stop for 15 s.
7/ Depress pedal twice.
8/ Repeat 5, 6, 7 up to 5 times, as necessary.
9/ If no-start, remove to warmer area, start and run the engine for at least 15 min before preparation for the next test.

Cold-Start Procedure for Ford Escort

1/ Ignition switch on.
2/ Wait 10 s (end of the seat belt buzzer).
3/ Depress pedal 6 times.
4/ Crank for 10 s -- foot off accelerator.
5/ If no-start, stop for 10 s.
6/ Depress pedal twice.
7/ Repeat 4, 5, 6 up to 5 times, as necessary.
8/ If no-start, remove to warmer area, start and run the engine for at least 15 min before preparation for next test.

APPENDIX C/ ENGINE PART MEASUREMENTS

1983 Ford Escort (methanol fuel)
Vehicle Number: 81-117-001-30Y
Engine Size: 1600 cc. 4 cyl.

Engine Part Measurements

Compression Test (psi)

Vehicle-Kilometres		Cylinder 1	Cylinder 2	Cylinder 3	Cylinder 4
6 164	Dry	175	178	160	180
	Wet	170	210	185	195
33 670	Dry	180	195	175	180
	Wet	200	200	195	200

Valve Clearance (mm)

	#1	#2	#3	#4
Intake	O.K.	O.K.	*out (1.05 - 1.10 mm)	O.K.
Exhaust	O.K.	O.K.	O.K.	O.K.

Crankcase Diameter (mm)

Vehicle-Kilometres		#1	#2	#3	#4
6 164	Vertical	47.910	47.895	47.895	47.895
	Horizontal	47.895	47.895	47.895	47.91
33 670	Vertical	47.900	47.900	47.900	47.900
	Horizontal	47.895	47.895	47.900	47.900

Note: Same at both ends of crank pin.

Camshaft Measurements (mm) Journal Diameter

Vehicle-Kilometres		#1	#2	#3	#4	#5	Specification
6 164	A	44.750	44.995	45.245	45.495	45.745	44.7625-45.1425
	B	44.745	44.995	45.245	45.500	45.740	
33 670	A	44.745	44.995	45.245	45.495	45.745	
	B	44.745	44.995	45.245	45.500	45.745	

Camshaft Lobe and Base (mm)

Vehicle-Kilometres		#1		#2		#3		#4		Specification (Lift)	
		Exhaust	Intake	Exhaust	Intake	Exhaust	Intake	Exhaust	Intake	Exhaust	Intake
6 167	Lobe	38.24	38.26	38.25	38.26	38.25	38.26	38.25	38.27	5.805	5.805
	Base	32.47	32.48	32.47	32.47	32.48	32.49	32.47	32.49	to	to
	Lift	5.77	5.78	5.78	5.79	5.77	5.77	5.78	5.78	5.678	5.678
33 670	Lobe	38.24	38.25	38.25	38.25	38.26	38.26	38.25	38.27		
	Base	38.46	32.48	32.47	32.47	32.48	32.47	32.47	32.48		
	Lift	5.78	5.77	5.78	5.78	5.78	5.79	5.78	5.79		

Note: Lift = Lobe - Base

Connecting Rod Diameter (mm)

Vehicle-Kilometres	Connecting Rod No.	In Crankshaft Plane		90 Degrees to Crankshaft Plane		Average
		Front	Rear	Front	Rear	
6 167	1 cyl.	47.990	47.975	48.005	48.010	47.9950
	2 cyl.	48.015	48.030	48.000	48.010	48.0138
	3 cyl.	47.990	47.980	48.035	48.035	48.0100
	4 cyl.	48.025	48.025	47.965	47.975	47.9975
33 670	1 cyl.	47.980	47.990	48.030	48.050	48.0125
	2 cyl.	47.960	47.970	48.030	48.050	48.00
	3 cyl.	47.980	47.970	48.0	48.01	47.9900
	4 cyl.	47.990	47.990	48.035	48.035	48.0125

Valve Tappet Lifter Diameter (mm)

Vehicle-Kilometres		#1		#2		#3		#4		Specification
		Exhaust	Intake	Exhaust	Intake	Exhaust	Intake	Exhaust	Intake	
6 167	Bore	22.24	22.23	22.23	22.23	22.23	22.23	22.24	22.24	22.25 ± 0.015
33 670	Tappet	22.20	22.21	22.20	22.21	22.2	22.21	22.21	22.21	22.212 - 22.20
6 167	Bore	22.24	22.23	22.23	22.23	22.23	22.23	22.24	22.23	
33 670	Tappet	22.20	22.20	22.20	22.20	22.20	22.20	22.20	22.20	

Valve Stem Diameter (mm)

Vehicle-Kilometres		#1		#2		#3		#4		Specifications	
		Exhaust	Intake	Exhaust	Intake	Exhaust	Intake	Exhaust	Intake	Exhaust	Intake
6 167	Top	8.01	8.03	8.01	8.035	8.01	8.03	8.005	8.035	8.017 to 7.999	8.043 to 8.025
	Bottom	8.01	8.03	8.01	8.035	8.01	8.03	8.005	8.030		
33 670	Top	8.00	8.02	8.00	8.020	8.00	8.02	8.00	8.025		
	Bottom	8.00	8.02	8.00	8.020	8.00	8.02	8.00	8.00		

Stem Height Above Top of Guide (mm)

Vehicle-Kilometres	Cylinder #1		Cylinder #2		Cylinder #3		Cylinder #4	
	Exhaust	Intake	Exhaust	Intake	Exhaust	Intake	Exhaust	Intake
6 167	22.24	22.23	22.23	22.23	22.23	22.23	22.24	22.24
33 670	35.20	38.85	34.92	36.01	35.21	35.93	34.95	35.97

Valve Guide Diameter (mm)

Note: Specifications are 8.063 - 8.094 inner diameter.

		Intake		Exhaust	
Vehicle-km		6 167	33 670	6 167	33 670
Cylinder #1	Top	8.065	8.080	8.055	8.080
	Bottom	8.063	8.080	8.063	8.160
Cylinder #2	Top	8.065	8.080	8.082	8.075
	Bottom	8.063	8.080	8.070	8.140
Cylinder #3	Top	8.060	8.080	8.063	8.070
	Bottom	8.045	8.080	8.067	8.250
Cylinder #4	Top	8.065	8.070	8.065	8.080
	Bottom	8.062	8.080	8.063	8.150

Piston Ring Width (mm)

Compression Ring	Cylinder 1		Cylinder 2		Cylinder 3		Cylinder 4		Specifications	
	A	B	A	B	A	B	A	B	A	
Top	1.580	1.580	1.580	1.580	1.580	1.580	1.580	1.580	1.59	1.998
Bottom	1.980	1.980	1.960	1.980	1.960	1.980	1.960	1.980	1.578	1.982

Piston Ring Groove Width (mm)

	Cylinder 1		Cylinder 2		Cylinder 3		Cylinder 4		Specifications
	A	B	A	B	A	B	A	B	
Top Groove	1.650	1.650	1.640	1.650	1.652	1.650	1.650	1.650	1.640 - 1.660
Bottom Groove	2.050	2.050	2.050	2.050	2.052	2.050	2.050	2.050	2.038 - 2.062

Oil Ring Groove Width (mm)

Cylinder 1		Cylinder 2		Cylinder 3		Cylinder 4		Specifications
A	B	A	B	A	B	A	B	
4.025	4.020	4.023	4.020	4.020	4.020	4.023	4.020	4.032 to 4.008

Compression Rings End Gap (mm)

Top Ring	Cylinder 1		Cylinder 2		Cylinder 3		Cylinder 4	
	A	B	A	B	A	B	A	B
Top of Cylinder Bore	0.610	0.480	0.55	0.50	0.559	0.50	0.483	0.480
Bottom of Cylinder Bore	0.533	0.460	0.533	0.480	0.50	0.480	0.432	0.460
Average	*0.572	0.470	*0.541	*0.490	*0.525	0.49	0.457	0.470

Note: A = measured at 6 167 km
B = measured at 33 671 km after new rings installed at 6167 km
* = out of specification

Specification is 0.30 to 0.50 mm

Bottom Ring End Gap (mm)

	Cylinder 1		Cylinder 2		Cylinder 3		Cylin der 4		Specifications	
Top of Cylinder Bore	A	B	A	B	A	B	A	B	A	B
	0.66	0.48	0.615	0.49	0.610	.48	0.584	0.48		
Bottom of Cylinder Bore	0.615	0.46	0.610	0.46	0.559	0.48	0.533	0.48		
Average	*0.637	0.47	*0.612	0.475	*0.585	0.48	*0.558	0.48	0.3 to 0.5	

*Out of specification

Piston (Steel Rail) End Gap (mm)

	Cylinder 1		Cylinder 2		Cylinder 3		Cylinder 4		Specifications
	A	B	A	B	A	B	A	B	
Top of Cylinder Bore	1.15	1.15	1.30	1.15	1.15	1.15	1.05	1.15	0.40 to 1.4
Bottom of Cylinder Bore	1.25	1.10	1.00	1.10	1.25	1.10	1.05	1.10	

Piston Diameter

Piston measurement position
(for diameter)

	Coded Red	Cylinder 1		Cylinder 2		Cylinder 3		Cylinder 4	
		A	B	A	B	A	B	A	B
90° to Piston Pin	Top Area	79.46	79.44	79.48	79.40	79.36	79.42	79.40	79.42
	Bottom Area	79.94	79.90	79.90	79.90	79.92	79.89	79.92	79.90
At Piston Pin	Top area	79.38	79.38	79.40	79.40	79.36	79.39	79.34	79.41
	Bottom area	79.42	79.39	79.32	79.36	79.32	79.37	79.34	79.37

NOTE: Specifications for Red Code are 79.915 - 79.900 mm
Specifications for Blue code are 79.945 - 79.930 mm

Cylinder Bore Diameters (mm)

Cylinder Number		Top of Ring		Above Ring Travel Area	
		A	B	A	B
1	Perpendicular	80.00	80.00	79.99	79.95
	Parallel	80.00	80.01	79.97	79.94
2	Perpendicular	80.00	80.05	79.99	79.97
	Parallel	80.00	80.00	79.98	79.96
3	Perpendicular	80.00	80.00	80.00	79.98
	Parallel	80.00	80.00	79.98	79.96
4	Perpendicular	80.00	80.00	80.00	79.98
	Parallel	80.00	80.00	80.00	79.98

Distributor Timing Advance Chart

With module disconnected. Test conducted on March 7, 1984.

Engine rpm	Timing without Vacuum
600	0
800	0
850 (idle speed)	-1
1000	-2
1200	-3
1400	-4
1600	-4
1800	-1
2000	1
2200	4
2400	4
2600	4
2800	4
3000	4
3200	4
3400	5
3600	5
3800	5
4000	5
4500	5

Vacuum at 2000 rpm (in. Hg)	Timing with Vacuum
0	0
1	0
2	3
3	7
4	10
5	16
6	19
7	21
8	24
9	25
10	25
12	25

Vehicle Reassemble
(after engine overhaul)
New rings, valves, spark plugs, seals, valve guides

New Valve Weight (g)

Cylinder	Intake	Exhaust
1	99.8641	86.6108
2	99.1521	86.4752
3	99.5648	86.5657
4	99.2471	86.6343

New Valve Stem Diameter (mm)

Cylinder	Intake	Exhaust
1	8.030	8.005
2	8.030	8.010
3	8.035	8.010
4	8.030	8.010